DIRECT TORQUE CONTROL OF SWITCHED RELUCTANCE MOTOR DRIVES

A Thesis submitted in partial fulfillment of the requirements for the degree of Master of Technology
in
Electrical Engineering
(Power Control & Drives)

By

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Dedicated to my beloved parents and sisters

National Institute of Technology

Rourkela

CERTIFICATE

This is to certify that the thesis entitled "**DIRECT TORQUE CONTROL OF SWITCHED RELUCTANCE MOTOR DRIVES**" submitted by **AMALENDU DASH** bearing **Roll No.210EE2225** in partial fulfillment of the requirements for the award of the degree of "**Master of Technology**" in Electrical Engineering specializing in "**Power Control and Drives"** at the National Institute of Technology, Rourkela is an authentic work carried out by his under my supervision. To the best of my knowledge and belief, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

Date:

Place:

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Amalendu Dash

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ACRONYMS

N_S	No. Of Stator Pole
N_r	No. Of Rotor Pole
m	No. Of Phases
L_a	Aligned Inductance
L_u	Un-aligned Inductance
β_s	Stator Pole Arc
β_r	Rotor Pole Arc
P_r	No. Of Rotor Pole
ψ	Flux linkage per phase
e	Induced emf
K_b	Emf constant
P_i	Instantaneous power input
P_a	Air gap power
T_e	Electromagnetic torque
k_p	Proportionality Gain
k_d	Derivative Gain
k_i	Integral Gain
$V_{\alpha s}$	α- axis Stator Voltage
$V_{\beta s}$	β- axis Stator Voltage
$V_{\alpha r}$	α- axis Rotor Voltage
$V_{\beta r}$	β- axis Rotor Voltage
$i_{\alpha s}$	α- axis Stator Current
$i_{\beta s}$	β- axis Stator Current
$i_{\alpha r}$	α- axis Rotor Current
$i_{\beta r}$	β- axis Rotor Current
L_s	stator inductance
L_r	Rotor inductance
L_m	Mutual inductance
R_S	Stator Resistance
R_r	Rotor inductance

$\psi_{\alpha s}$	α- axis Stator Flux Linkage
$\psi_{\beta s}$	β- axis Stator Flux Linkage
$\psi_{\alpha r}$	α- axis Rotor Flux Linkage
$\psi_{\beta r}$	β- axis Stator Flux Linkage
$\vec{V}_s$	Voltage space vector
V_{ds}	DC link voltage of inverter
σ	Leakage co-efficient of the motor
p	Number of pole pairs

ABSTRACT

The Switched Reluctance Motor is an old member of the electric machine family. It receives the significant response from industries in the last decade because of its simple structure, ruggedness, high reliability, inexpensive manufacturing capability and high torque-to-mass ratio. The Switched Reluctance Motor consists a salient pole stator with concentrated coil and salient pole rotor, which have no conductors and magnets. The motor's doubly salient structure makes its magnetic characteristics highly nonlinear. This work briefly describes the constructional features, principle of operation and mathematical model of Switched Reluctance Motor. However the application of SRM has been limited because of their large torque ripple, which produces noise and vibration in the motor.

In order to solve these problems, a Direct Torque control (DTC) technique is used in order to control the torque of the Switched Reluctance Motor. By using this method we can well regulate the torque output of the motor with in hysteresis band.

CHAPTER 1

1. INTRODUCTION

1.1 Overview:

The functionality of Switched Reluctance Motor is already known for more than 150 years, but only some vast improvements of the power electronics drive technologies have made a great success of adjustable speed drives with Switched Reluctance Motor.

Due to enormous demand for variable speed drives and development of power semiconductors the conventional reluctance machine has been come into picture and is known as Switched Reluctance Machine. The name “Switched Reluctance”, first used by one of the authors of [1], describes the two features of the machine configuration (a) switched,(b) reluctance.

Switched word comes into picture because this machine can be operated in a continuous switching mode. Secondly reluctance word comes into picture because in this case both stator and rotor consist of variable reluctance magnetic circuits or we can say that it have doubly salient structure.

A SRM has salient poles on both stator and rotor. Each stator pole has a simple concentrated winding, where the rotor does not contain any kind of winding or permanent magnet [2]-[4]. It is made up of soft magnetic material that is laminated steel. Two diametrically opposite windings are connected together in order to form the motor phases. During the rotor rotation a circuit with a single controlled switch is sufficient to supply an unidirectional current for each phase. For forward motoring operation the stator phase winding must be excited when the rate of change of phase inductance is positive. Otherwise the machine will develop breaking torque or no torque at all. As SRM has simple, rugged construction, low manufacturing cost, fault tolerance capability and high efficiency the SRM drive is getting more and more recognisation among the electric drives. It also have some disadvantages that it requires an electronic control and shaft position sensor and double salient structure causes noise and torque ripple. SRMs are typically designed in order to achieve a good utilization in terms of converter rating.

1.2 Advantages, Limitations and Applications of SRM.

1.2.1 Advantages:

In a SRM, only stator consists of phase windings while rotor is made of steel laminations without any conductors or permanent magnet. So, the SRM has several advantages over conventional motors.

(a) SRM drive maintain high efficiency over wide speed and load range because as there is no winding present on rotor. So, cu loss, heat loss reduces in this case. So, efficiency of SRM drive increases.

(b) As there is no windings or permanent magnets on its rotor, and there are no brushes on its stator, along with its salient rotor poles make the SRM's rotor inertia less than that of its conventional motor. So, SRM can accelerate more quickly.

(c) As it does not have a brush commutator mechanical speed limit, no winding or permanent magnet present on rotor. So, it can run up to high speeds. It can also operate at low speeds providing full rated torque.

(d) As there are no windings or permanent magnet present on rotor so, the cost of the SRM drive reduces.

(e) It follows four quadrant operations; it can run forward or backward direction. We can call it as motoring or generating mode of operation.

(f) Rugged construction suitable for high temperature and vibrating zone.

(g) Most losses that will occur in SRM that must be in stator which can easily be cooled.

(h) Torque produced by SRM is independent of the polarity of the phase current, allowing the use of simplified power converters with a reduced number of semi converter switches.

1.2.2 Limitations of SRM:

Along with the above advantages SRM drives also has some limitations. Following are some of the limitation of SRM drive.

(a) As SRM drive is having doubly salient structure which causes inherent torque ripple and acoustic noise.

(b) The converter which is used in case of SRM drive that requires high KVA rating.

(c) As the inductance of the winding is very high and it is required to remove the stored energy after excitation so, a large energy removal period is usually required limiting the maximum current to relatively low range.

(d) SRM drive cannot operate directly from ac or dc supply and require current pulse signal for torque production.

The requirement of rotor position sensor, higher torque pulsation [5-7] and acoustic noise [8-10] are the major drawbacks of SRM drive and that may limit the SRM in some application.

1.2.3 Application of Switched Reluctance Motor Drives:

SRM drive has greater potential in motion control because it will give high performance in harsh condition like high temperature and dusty environment [11-13].

(1) Electric Vehicles

(2) Aerospace [14,15]

(3) Household appliances like washing machine and vacuum cleaners [16].

(4) Variable speed and servo type application

1.2.4 Direct Torque Control of Switched Reluctance Motor*:*

As SRM drive is having doubly salient structure thus it has high torque ripple and acoustic noise problem. Various proposed methods are used in order to reduce the torque ripple. One of the methods is by skewing the rotor which can minimize the torque ripple [20], [21]. Similarly another method is direct torque control method of SRM. DTC is the advanced vector control method. This method is used to control the torque of SRM through the control of the magnitude of flux linkage and change in speed (acceleration or deceleration) of the stator flux vector.

1.3 Motivation

1.3.1 Switched Reluctance Motor:

It works under reluctance principle. The main difference between the synchronous reluctance machine and switched reluctance machine is that, if the excitation of synchronous machine gets fail then it will act like synchronous reluctance machine. So synchronous reluctance machine can only run if both the stator and rotor poles are same. But the beauty of Switched Reluctance Motor is that even though the poles of stator and rotor are different then also it will rotate by following the reluctance principle. The first aim of SRM model is that whether it is capable of representing both flux linkage and inductance profile characteristics. The second aim is to design the machine which is capable of operating over a wide speed range in all four-quadrants of the torque-speed graph. We can also achieve high performance with SRM drives which offers high efficiency by using one of the optimization technique [11,12]. The third aim of the research is to improve the reliability, accurate positioning and evaluation of performance characteristics.

1.3.2 Direct Torque Control of Switched Reluctance Motor:

In order to improve the dynamic performance of switched reluctance motor drives vector control technique is preferred. But the main disadvantage of vector control technique is complexity of coordinate transformation. This problem can be solved by using advanced vector control technique which is known as direct toque control technique.

1.4 Objectives

i. To study principle of operation of switched reluctance motor drive and obtain the mathematical model of SRM.
ii. In order to design the various phases of SRM and observe what are the major changes that may be occurred in various phases of SRM.
iii. To observe by changing the turn-on and turn-off angle how its characteristic changes.
iv. To observe by using PID controller how the reference speed track the actual speed.
v. To implement an advance vector control technique known as DTC technique in order to reduce the torque ripple in case of SRM.

1.5 Thesis Outline

This thesis contains six chapters and that are given below.

Chapter 1	Presents a brief idea about switched reluctance motor drive. It contains the introduction, advantages, disadvantages, application, control strategy, motivation and objectives.
Chapter 2	The principle of operation of SRM, elementary operation of SRM, Converter topology for SRM drive, various voltage state.
Chapter 3	Mathematical modelling of SRM, its torque equation, PID controller, block diagram representation of SRM.
Chapter 4	Simulation modelling and results of 3-phase,4-phase,5-phase switched reluctance motor drive.
Chapter 5	Direct Torque Control of 3-phase switched reluctance motor drive and its simulation results.
Chapter 6	Gives the overall conclusion and scope for future work of the project.

CHAPTER 2

2. PRINCIPLE OF OPERATION OF THE SWITCHED RELUCTANCE MOTOR

2.1 Introduction

The machine operation and salient feature can be deduced from the torque expression. The torque expression is nothing but the relationship between machine flux linkages or inductance and rotor position. The torque v/s speed characteristics of the machine operation in all of its four quadrants can be derived from the inductance v/s rotor position characteristics of the machine. Switched Reluctance Machine can be designed of any phases. For single phase machine it have low performance but high volume application.

2.2 Switched Reluctance Motor Configuration

Switched Reluctance Motor can be made up of laminated stator and rotor cores with N_s =2mq poles on the stator and N_r poles on rotor.

Where m is number of phases and each phase made up of concentrated windings placed on 2q stator poles. Switched reluctance motor is having salient pole stator with concentrated winding and salient pole rotor with no winding or permanent magnet. As both stator and rotor have salient pole structure, hence we can say that switched reluctance motor is having doubly salient structure which is single excited with different number of stator and rotor poles. It is constructed in such a manner that in no way the rotor poles in a position wher the torque due to current in any phase is zero. The common stator/rotor pole configuration are 6/4,8/6,10/8. In stator the coils on two diametrically opposite poles are connected in series in order to form single phase. So, 6/4 stator/rotor pole configuration means that represent the 3-phase configuration of switched reluctance motor drive. Similarly 8/6 and 10/8 stator/rotor pole configuration represents the 4 and 5 phase configuration of switched reluctance motor drive.

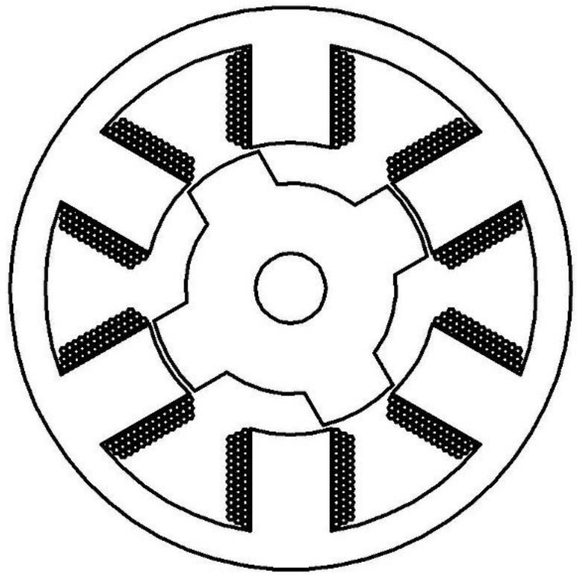


Fig.2.1 6/4 switched reluctance motor configuration

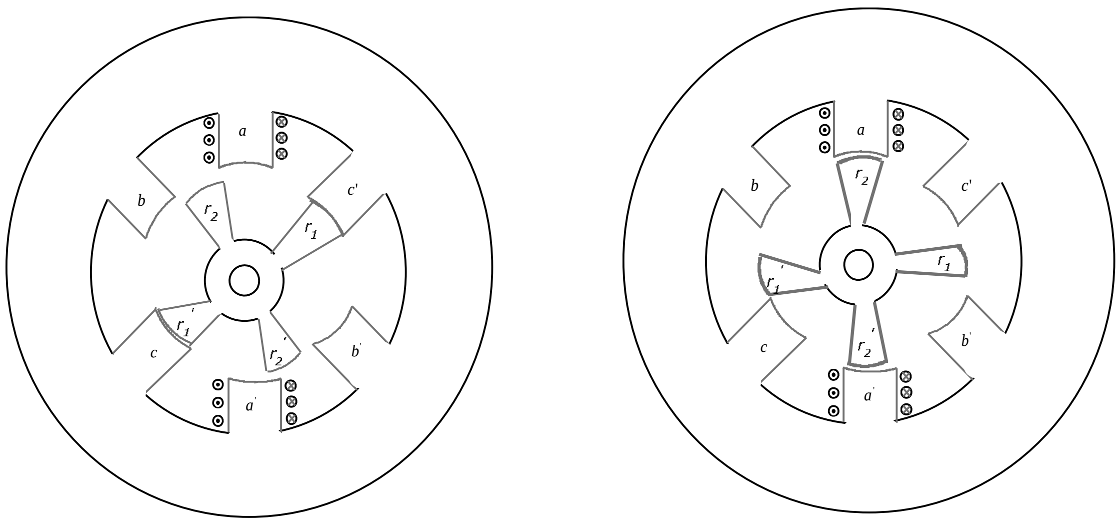
Similarly for 8/6 SRM configuration it have 8 stator and 6 rotor poles and in 10/8 SRM configuration it have 10 stator pole and 8 rotor poles are present.

2.3 Principle of operation:

An electromagnetic system in order to form stable equilibrium position gives rise to minimum magnetic reluctance is the main principle of operation of switched reluctance motor. When the two diametrically opposite poles are excited, the nearest rotor poles are attracted towards each other, in order to produce torque. When the two rotor poles gets aligned with the stator pole then it gets de energise and the adjacent stator pole gets energise to attract another pair of rotor poles. According to this principle switched reluctance motor gets run.

When both the stator and rotor poles gets aligned with each other then that position is known as aligned position. The phase inductance during the aligned position reaches its maximum value known as L_a as the reluctance reaches its minimum value. The phase inductance decreases gradually as the rotor poles move away from its aligned position. When the rotor poles get completely unaligned or misaligned from stator poles then the phase inductance at that moment reaches its minimum value known as L_u. Reluctance in this case reaches its maximum value.

2.4 Elementary Operation of Switched Reluctance Motor:



(a) **(b)**

Fig.2.2 Operation of SRM (a) Phase ‘c’ aligned (b) Phase ‘a’ aligned

- In the fig.(a) the rotor poles r_1 & r_1' and stator poles C & C' are aligned. By applying the current to phase ‘a’ with current direction as shown in fig. the flux is established through stator poles a & a‘ and rotor poles r_2 & r_2' which tend to pull the rotor poles r_2 & r_2' towards the stator poles a & a‘ respectively. When they are aligned then stator current of phase a gets turned off as shown in fig. (b).

- Now the stator winding b is excited, pulling r_1 & r_1' towards b & b' in a clockwise direction. Likewise, energization of c phase winding results in the alignment of r_2 & r_2' with c & c' respectively.
- It takes 3 phase energization to move the rotor by 90^0, and one revolution of rotor movement is affected by switching currents in each phase as many times as there are

no. of rotor poles. The switching of currents in the sequence of acb results in the reversal of the rotor rotation.

2.4 The Relation Between Inductance And Rotor Position (Non Linear Analysis):

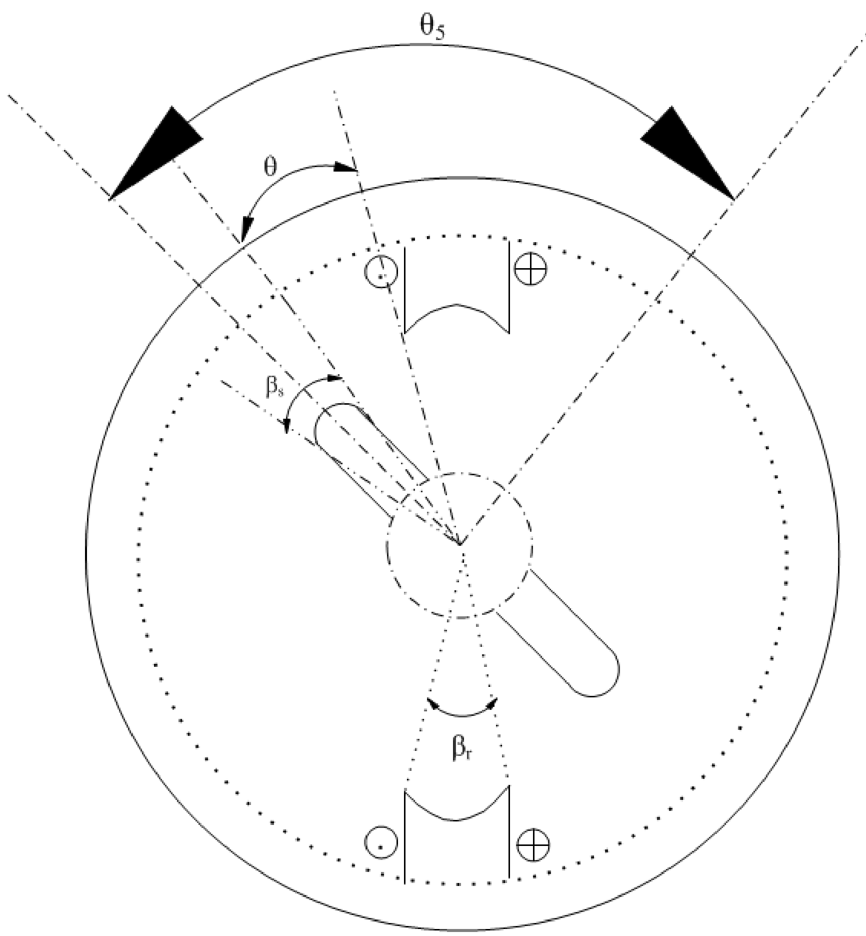


Fig.2.3 Basic Rotor Position in A Two Pole SRM

The relationship between the flux linkages and the rotor position as a function of current gives rise to the characteristics of torque. The stator and rotor pole arc and the number of rotor poles helps to determine the changes in the inductance profile.

Followings are some angles that can be derived from figures 2.3 and figure 2.4.

$$\theta_1 = \frac{1}{2}\left[\frac{2\pi}{p_r} - (\beta_s + \beta_r)\right] \quad \text{.......................................} \quad (2.1)$$

$$\theta_2 = \theta_1 + \beta_s \quad \text{...} \quad (2.2)$$

$$\theta_3 = \theta_2 + (\beta_r - \beta_s) \quad \text{..} \quad (2.3)$$

$$\theta_4 = \theta_3 + \beta_s \quad \text{...} \quad (2.4)$$

$$\theta_5 = \theta_4 + \theta_1 = \frac{2\pi}{p_r} \quad \text{...} \quad (2.5)$$

Where β_s and β_r are stator and rotor pole arcs respectively and p_r is the number of rotor poles.

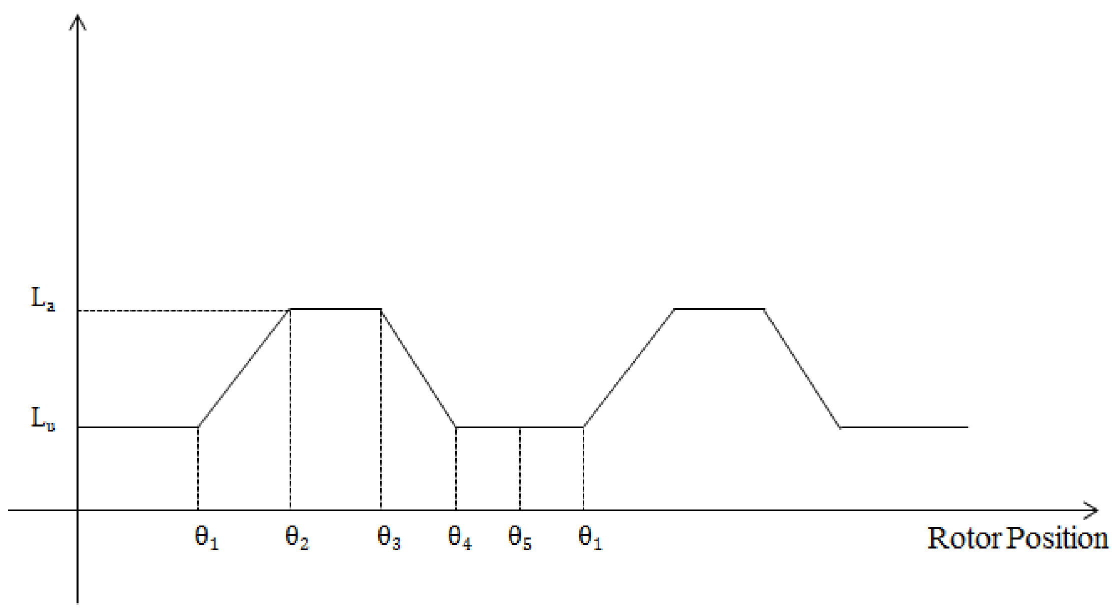


Fig.2.4 Inductance Profile for Switched Reluctance Motor

1. **0-θ_1 and θ_4-θ_5:** In this region both the stator and rotor poles are not aligned with each other. Thus inductance in this case is minimum and almost constant. The inductance in this portion is minimum and is known as unaligned inductance which is also called as L_u. This region does not contribute any role in torque production.

2. **θ_1-θ_2:** In this region the rotor pole starts overlapping on to the stator pole. So, the flux path in this region is predominantly through stator and rotor laminations. So, the inductance gets increased with respect to rotor position and that gives rise to positive slope. During this period the current produced in the winding produces the motoring torque or positive torque. When the rotor pole completely overlaps the stator pole at that period this region comes to an end.

3. **θ_2-θ_3:** In this region the rotor pole completely overlap the stator pole. This region gives rise to predominantly high flux path. So, effect on inductance in this region is very high and it is constant. This inductance is also known as aligned inductance and can be represented as L_a. As torque is the function of rate of change of inductance with respect to rotor position and in this region inductance is constant . So, torque is zero in this case even though current present in this interval.
4. **θ_3-θ_4:** In this region the rotor pole is moving away from the stator pole. This region is very much similar with the region like θ_1-θ_2 but in reverse manner. In this case as the misalignment of rotor pole increases with respect to stator pole the inductance get decreases and it gives rise to negative slope. So, the negative torque will be produced in this region, which is nothing but the generation of electrical energy from the mechanical input to the switched reluctance machine.

So, from the above analysis we will get that it is not possible to achieve the ideal inductance profile in actual motor due to saturation.

2.5 Converters For Switched Reluctance Motor Drive:

2.5.1 Power Converter Topology:

In order to achieve the smooth rotation and optimal torque output the phase-to-phase switching in the switched reluctance motor drive is required with respect to rotor position. The phase-to-phase switching logic can only be realized by using the semi converter device. We can also say that the power semi converter device topology put a great impact on switched reluctance motor's performance.

As the torque produced in the switched reluctance motor drive is independent of the excitation current polarity. So, it requires only one switch per phase winding. Where as for other ac machine it requires two switches per phase in order to control the current. For ac motor the winding is also not present in series with the switches, which gives rise to irreparable damage in shoot-through fault. But in case of switched reluctance motor as the winding is present in series with the switch, so, during shoot-through fault the rate of rise in current can be limited or reduced by using winding inductance and provides time to protective relay in order to isolate the faults. Switched reluctance motor drive is more reliable because in this case all the phases are independent of each other. Even though if some problem will occur to switched reluctance motor and one winding gets damaged then also switched reluctance motor can provide the uninterrupted operation with reduced power output.

2.6 Asymmetric Bridge Converter:

In case of switched reluctance motor, we are using the number of half bridge converters which are same as the number of phases. So, as one phase of the switched reluctance motor is connected with the asymmetric bridge converter, similarly the rest are also connected. For example for three phase switched reluctance motor we are using three half bridge converter because from three half bridge converter we are getting six outputs and at the input of switched reluctance motor it have six input ports. As shown in figure below for each phase we are using asymmetric bridge converter which contain two IGBT's and two diodes and the phase winding is connected between them. When both Sa1 and Sa_2 switch gets turn on then current will circulate through phase 'A'. But when current exceeds the commanded value then Sa1 and Sa_2 gets turned off. At that moment energy stored in the winding will keep the current in the same direction by making D_1 and D_2 forward bias. So, the winding gets discharge and this will decrease the current below the commanded value.

Similarly the other phases are also operated like phase ‘A’ operated. Following is the complete diagram of the inverter circuit that is used for switched reluctance motor drive.

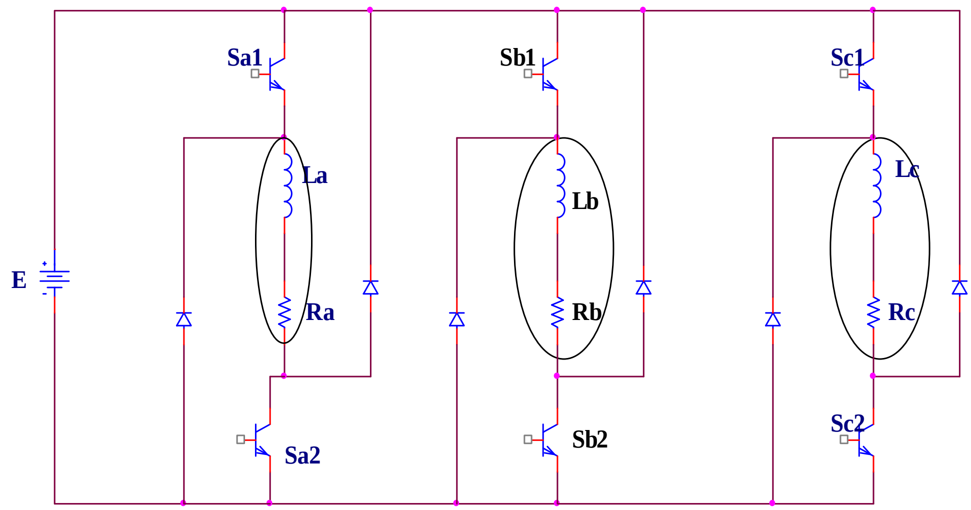


Fig.2.5 Asymmetric H-bridge Drive Circuit For SRM

The above fig. represent the asymmetric H-bridge for SRM.’L’ and ‘R’ denote inductance and resistance of the phase winding. The operation of the above fig. can be explained below.

Let say the rotor pole r_1 and r_1' is aligned with the stator pole c and c' then now S_{a1} and S_{a2} are turned on in order to excite the a-phase so as to produce the rotation in the positive direction. Reluctance torque is generated so that stator pole a, a' and rotor pole r_2, r_2' face each other, and the rotor rotates in clockwise direction. Then other phases are excited so as to align the next stator pole to rotor pole and in this manner the switched reluctance motor starts rotating.

The switched reluctance motor torque ‘T’ is generally expressed as follows assuming a linearly magnetic circuit with i_a, i_b and i_c denoting the respective phase currents.

$$T = \frac{1}{2}\left(\frac{\partial L_a}{\partial \theta} i_a^2 + \frac{\partial L_b}{\partial \theta} i_b^2 + \frac{\partial L_c}{\partial \theta} i_c^2 \right) \qquad (2.6)$$

This equation effective only when the magnetic circuit is linear.

2.7 Stator Current Control By Modified Hysteresis Band Control:

The asymmetric H-bridge shown in figure can apply a three level voltage to the stator winding i.e. (+E,0,-E).

Positive voltage mode: When both switches S_{a1} and S_{a2} are turned on, source voltage E is applied to the winding. As a result winding current increases**.** In this case voltage V=E and current flows in downward direction as shown in the below figure.

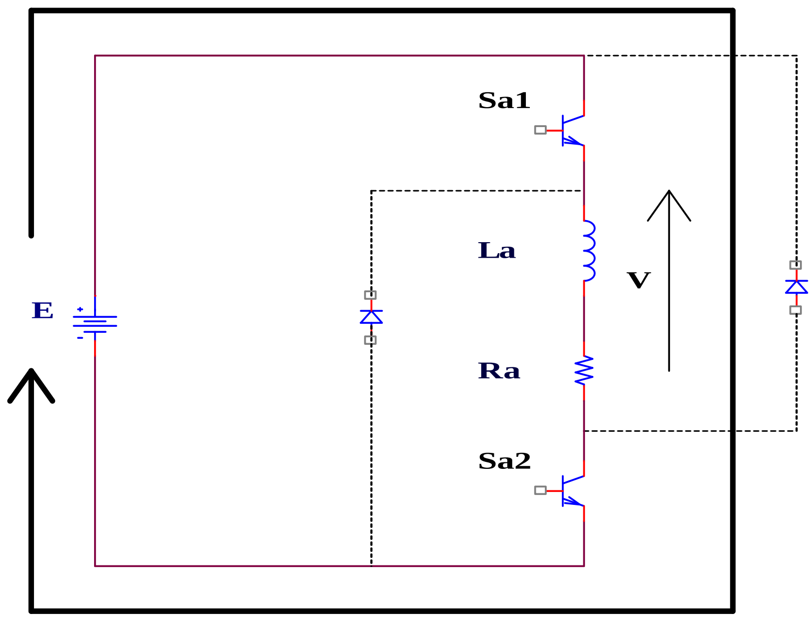


Fig.2.6(a) Positive voltage mode

Negative Voltage Mode: When both switches S_{a1} and S_{a2} are turned off while current flows in the winding, the two diodes conduct electricity voltage –E is applied to the winding and the current decreases. In this case voltage V=-E and current direction remains same but its value reduces.

Return Current Mode: Either of switches S_{a1} and S_{a2} is turned off while current flows in the winding. When S_{a1} turned off, the diode shown in the above diagram conducts electricity. Zero voltage is applied across the winding and current decreases. However this decrease is smaller than in the negative voltage mode.

As inductor is a storing device in this mode it discharges through one of the switch and diode. So voltage applied across phase winding is zero, but the current direction remains same. So only unipolar current produces inside switched reluctance motor in order to produce unidirectional torque.

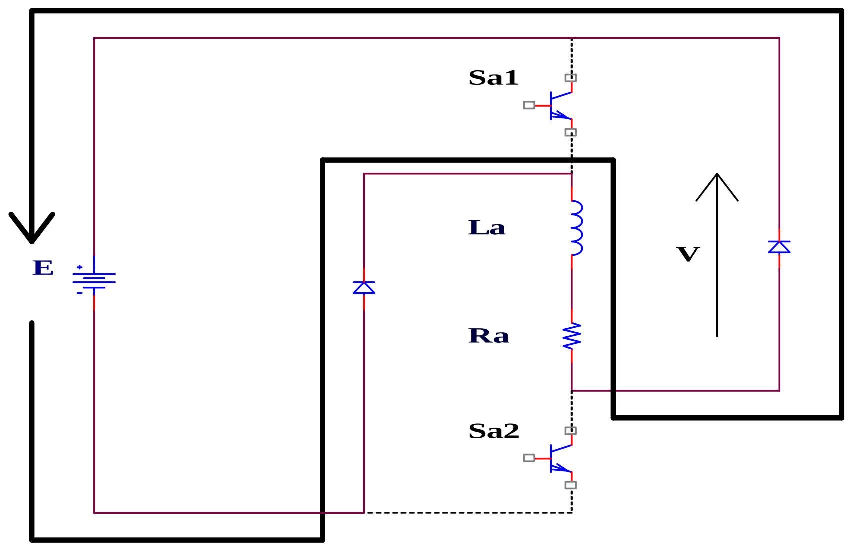


Fig.2.6(b) Negative Voltage Mode

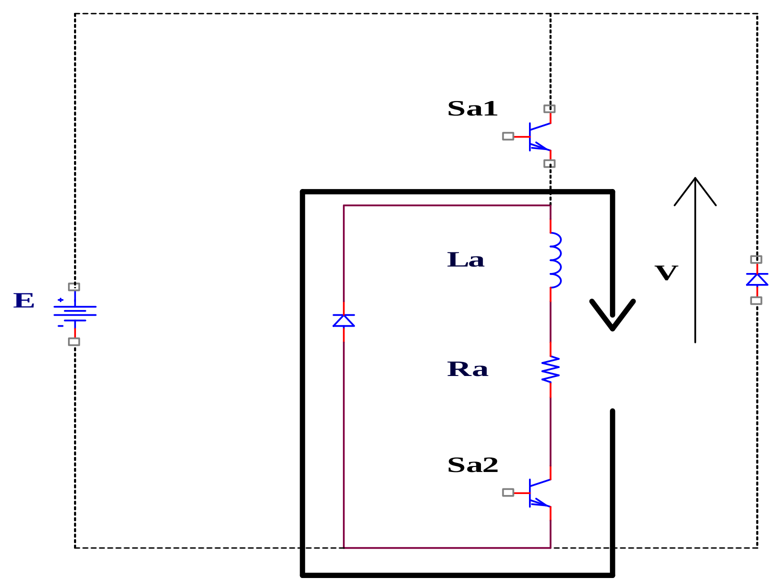


Fig. 2.6(c) Return Current Mode

CHAPTER 3

3. MATHEMATICAL MODELLING AND CONTROL OF SWITCHED RELUCTANCE MOTOR DRIVE

3.1 Mathematical Modeling of Switched Reluctance Motor Drive

The equivalent circuit for the switched reluctance motor can be derived by neglecting the mutual inductance between the phases as follows. Applied voltage to a phase can be derived as the sum of the resistive voltage drop and the rate of change of flux linkages with respect to time and it is given as

$$V = R_s i + \frac{d\psi(\theta, i)}{dt} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.1)}$$

Where 'R_s' is the resistance per phase and 'ψ' is flux linkage per phase.

$$\psi = L(\theta, i) i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.2)}$$

Where 'L' is the inductance dependent on the rotor position & the phase current. The phase voltage equation is given by,

$$\begin{aligned} V = R_s i + \frac{d\{L(\theta,i)i\}}{dt} &= R_s i + L(\theta,i)\frac{di}{dt} + i\frac{d\theta}{dt}.\frac{dL(\theta,i)}{d\theta} \\ &= R_s i + L(\theta,i)\frac{di}{dt} + \frac{dL(\theta,i)}{d\theta}\omega_m i \end{aligned} \qquad \text{(3.3)}$$

In this equation all the three terms on the right hand side represent the resistive voltage drop, inductive voltage drop and induced emf respectively and the result is equivalent to the series excited dc motor voltage equation.

The induced emf 'e' is obtained as,

$$e = \frac{dL(\theta, i)}{d\theta}\omega_m i = k_b \omega_m i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.4)}$$

Where K_b may be construed as an emf constant similar to that of dc series excited machine and is given as,

$$k_b = \frac{dL(\theta, i)}{d\theta} \quad \text{.......................................} \ (3.5)$$

Substituting for flux linkages in the voltage equation and multiply with the current results in instantaneous i/p power given by,

$$P_i = Vi = R_s i^2 + i^2 \frac{dL(\theta, i)}{dt} + L(\theta, i) i \frac{di}{dt} \quad \text{............} \ (3.6)$$

So, the equivalent circuit diagram for single phase SRM is given by,

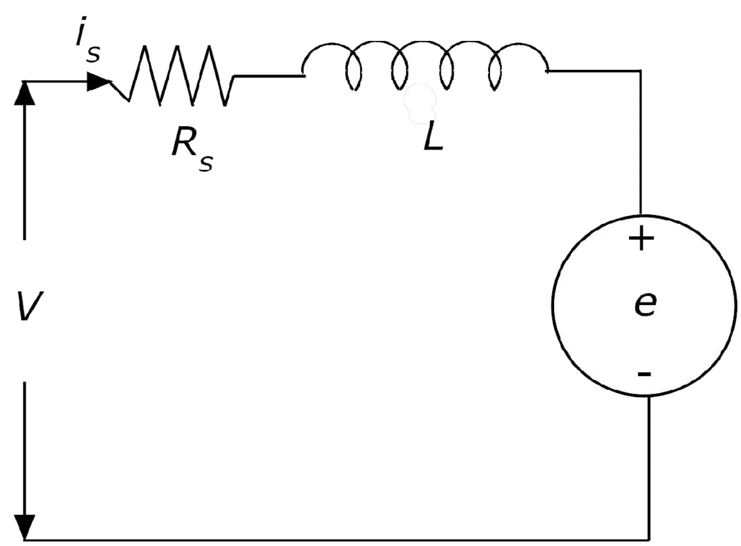


Fig.3.1 Single-Phase Equivalent circuit of Switched Reluctance Motor

In order to get meaningful inference the above equation need to express with known variables

$$\frac{d}{dt}\left(\frac{1}{2} L(\theta, i) i^2\right) = L(\theta, i) i \frac{di}{dt} + \frac{1}{2} i^2 \frac{dL(\theta, i)}{dt} \quad \text{.........} \ (3.7)$$

Substituting the above equation into (3.6) then we will get,

$$P_i = R_s i^2 + \frac{d}{dt}\left(\frac{1}{2} L(\theta, i) i^2\right) + \frac{1}{2} i^2 \frac{dL(\theta, i)}{dt} \quad \text{.......} \ (3.8)$$

Where, 'P_i' is the instantaneous power input which can be expressed as the sum of the winding resistive losses represented as $R_s i^2$, the rate of change of field energy i.e $\frac{d}{dt}\left(\frac{1}{2}L(\theta,i)i^2\right)$ and air gap power 'P_a' i.e represented as $\frac{1}{2}i^2\frac{dL(\theta,i)}{dt}$.

Time can also be represented in terms of rotor position and speed which is given below,

$$t = \frac{\theta}{\omega_m} \quad \text{..} \quad (3.9)$$

The air gap power can be represented as,

$$P_a = \frac{1}{2}i^2\frac{dL(\theta,i)}{dt} = \frac{1}{2}i^2\frac{dL(\theta,i)}{d\theta}\bullet\frac{d\theta}{dt} = \frac{1}{2}i^2\frac{dL(\theta,i)}{d\theta}\omega_m \quad (3.10)$$

The air gap power can also be represented as the product of the electromagnetic torque and rotor speed and is given by,

$$P_a = \omega_m T_e \quad \text{.....................................} \quad (3.11)$$

By equating the above two equation we will get,

$$T_e = \frac{1}{2}i^2\frac{dL(\theta,i)}{d\theta} \quad \text{..............................} \quad (3.12)$$

So, this shows that the electromagnetic torque is independent of current direction as T_e is directly proportional to i^2 . So, whatever may be the current value positive or negative the torque it will produce the unidirectional torque. But T_e is directly proportional to $\frac{dL(\theta,i)}{d\theta}$. So, if $\frac{dL(\theta,i)}{d\theta} > 0$ then, it will produce positive torque and electrical power is converted into mechanical power output (motoring) and if $\frac{dL(\theta,i)}{d\theta} < 0$ then, it will produce the negative torque and mechanical power is converted into electrical power (generating).

This completes the development of the equivalent circuit and equation for evaluating electromagnetic torque and input power to the switched reluctance motor for both dynamic and steady state operation [1].

3.2 PID Controller:

Due to simple control structure, Easy of design and inexpensive cost the conventional proportional-integral-derivative (PID) controller is most widely used in the industry. More than 90% of the control loops were of the PID types. As the formulas of PID controller are very simple and can be easily adopted by various controlled plant.

PID controller helps to correct the error between the reference variable and the actual variable. So, that the system can adjust the process accordingly. The general structure of PID controller is given below.

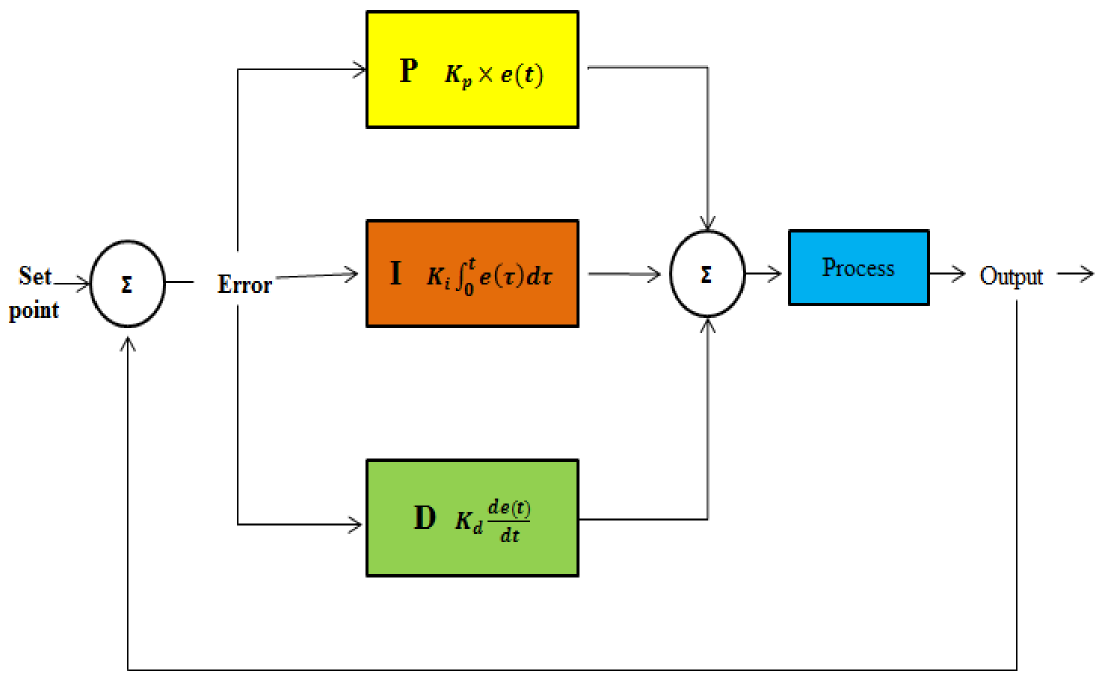


Fig.3.2 Structure of PID controller

For PID control the actuating signal consists of proportional error signal added with derivative and integral of the error signal.

The transfer function for the above block diagram i.e for PID controller is given as,

$$G_{PID} = k_p\left(1 + sk_d + \frac{k_i}{s}\right) \quad \text{……………} \quad (3.13)$$

Where 'k_p' can be represented as proportionality gain, 'k_d' as derivative gain constant and 'k_i' as the integral gain constant.

3.3 Function of Proportional-Integral-Derivative Controller:

3.3.1 Proportional Gain Constant:

In proportional control the actuating signal for the control action in control system is proportional to the error signal. The error signal is being the difference between the reference input signal and the feedback signal obtained from the output.

For satisfactory performance of a control system a convenient adjustment has to be made between the maximum overshoot and steady state error. By the help of proportional constant without sacrificing the steady state accuracy, the maximum overshoot can be reduced to same extent by modifying the actuating signal.

3.3.2 Integral Gain Constant:

For integral control action the actuating signal consists of proportional-error signal added with integral of the error signal.

By the help of an integrator, it reduces the steady state errors through low frequency compensation. By the help of this integral term the actual variable will track the reference variable more quickly.

3.3.3 Derivative Gain Constant:

For the derivative control action the actuating signal consists of proportional error signal added with derivative of the error signal.

By the help of a differentiator it improves the transient response through high frequency compensation. The steady state error is not affected by derivative control action. As the derivative of the error is used in actuating signal and as such if the error varies with time, then in that case the derivative control reduces the error.

So, PID control combines the advantages of proportional, derivative and integral control actions. In a closed loop system by changing one of the variable from k_p, k_d, k_i how the effect of other two variables will change that can be summarized in the table below.

Gain/Effect	Rise Time	Over Shoot	Settling Time	Steady State Error
k_p	Decrease	Increase	Small change	Decrease
k_i	Decrease	Increase	Increase	Eliminate
k_d	Small change	Decrease	Decrease	Small change

Table 3.1 Effects of k_p, k_d, k_i on a closed loop system

3.4 Block Diagram Representation of Switched Reluctance Motor Drive:

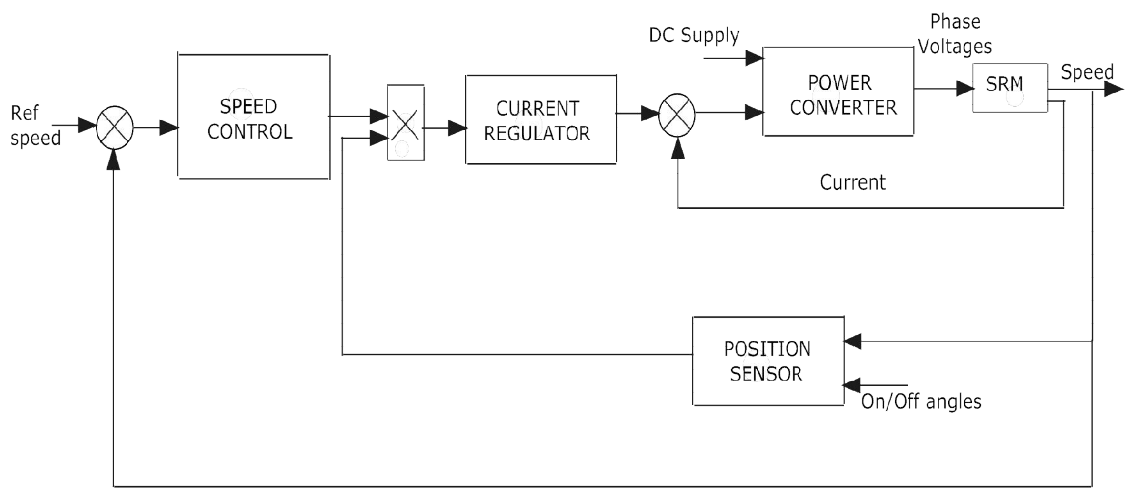


Figure.3.3 BLOCK DIAGRAM OF TRADITIONAL FEEDBACK CONTROL

This will give the closed loop control of switched reluctance motor. So, the actual speed will track the reference speed. So, machine will always remain in synchronism. In place of speed controller we are using PID controller and the output of this we are getting the error signal. That will move to the multiplexer along with θ which gives the reference current signal, this should be compared with the actual current signal in order to get the error current signal that is to be used as the gate pulse to the power converter. For 3-phase machine we are using 3 half bridge converters, for 4-phase '4' and for 5-phase '5' half bridge converters are used in order to get required amount of input to switched reluctance motor.

CHAPTER 4

4. MODELLING AND SIMULATION OF SRM DRIVE

4.1. Switched Reluctance Motor Specification:

Stator Resistance	: 0.01 ohm/phase
Friction	: 0.01 N m s
Inertia	: 0.0082 $kg.m^2$
Initial Speed	: 0 rad/sec
Position	: 0 rad
Unaligned Inductance	: 0.7 mH
Aligned Inductance	: 20 mH
Maximum Current	: 450 Amps
Maximum Flux Linkage	: 0.486 Weber-turn

4.2. Modelling of Three Phase Switched Reluctance Motor Drive:

In figure 3.3 that is the block diagram of switched reluctance motor, we are using the speed controller. Here the speed controller is nothing but the PID controller whose input is the speed error that is the difference between the speed reference and the filtered speed feedback signal and its output is unmodified torque command. Then that torque command goes to current command controller and feedback from position sensor gives rise to reference current that compare with the actual current signal that will feedback from Switched reluctance motor output gives the current error signal that goes to hysteresis band controller. That signal acting as the gate signal for converter. A dc supply has given to converter that converts to 2 level ac signals. Here we use 3 half bridge converters in order to produce 3 phase ac signal. That should be the input for Switched reluctance motor. At Switched reluctance motor output we are getting flux linkage, current, output torque as well as actual speed of motor.

4.2.1 Simulation Results for Three Phase Switched Reluctance Motor:

Various characteristics for 3-phase switched reluctance motor has given below,

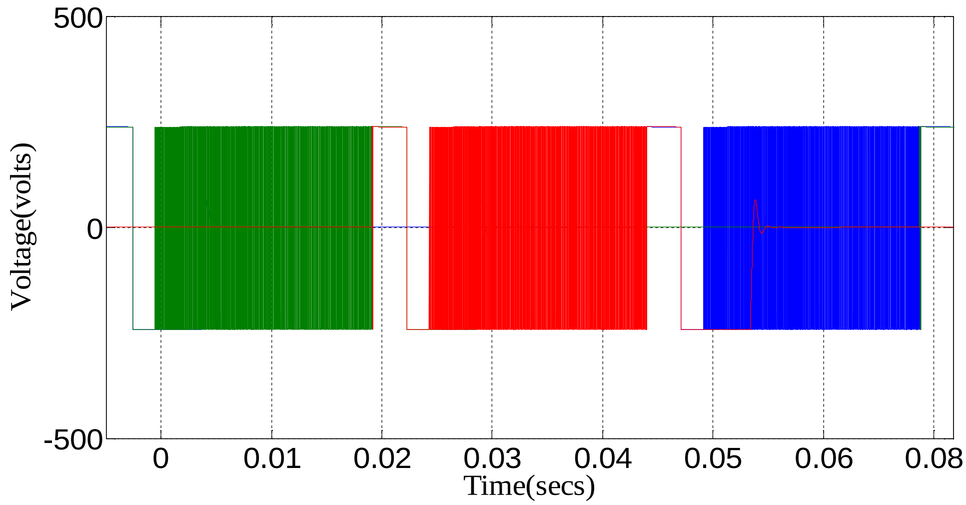


Figure.4.1. Voltage v/s Time characteristics

This is nothing but the output voltage of converter which becomes the input voltage for the three phase switched reluctance motor drive. This shows that the three phase voltages are 120^0 apart from each other.

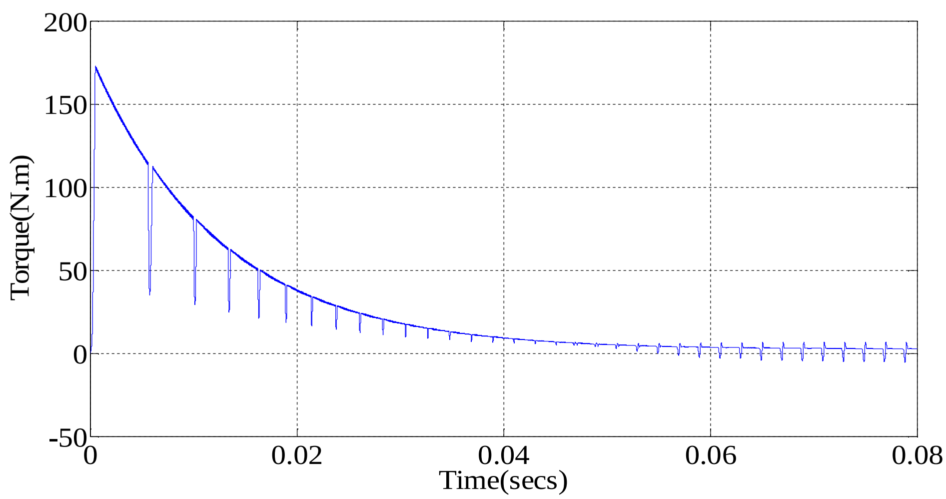


Figure.4.2 Torque v/s Time characteristics

Here torque is directly proportional to square of the current, so, torque is independent of current direction but it depends upon the $\frac{dL}{d\theta}$. If it is positive then torque is positive otherwise the torque is negative. This torque contains lots of noise and harmonics.

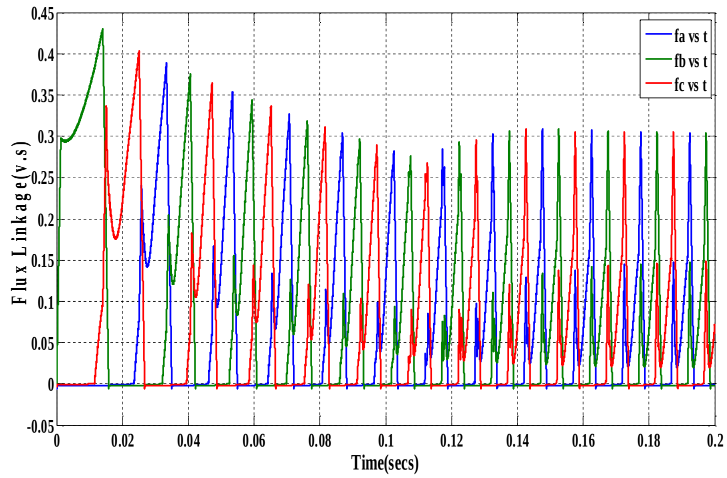


Figure.4.3 Flux Linkage v/s Time characteristics

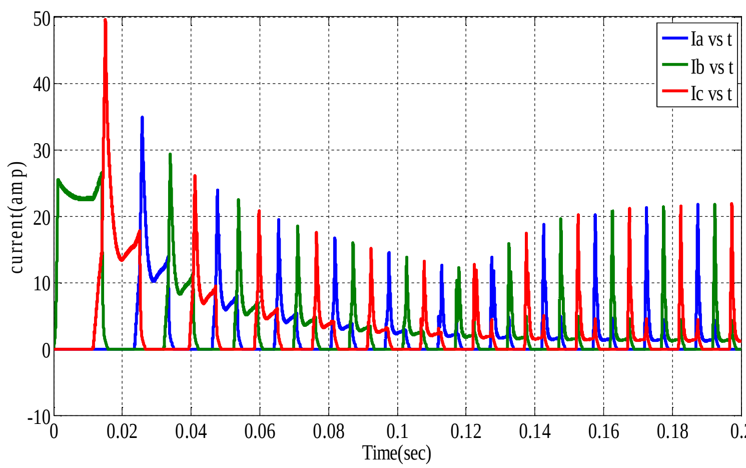


Figure.4.4 Current v/s Time characteristics

Here as flux linkage and currents are proportional to each other so as flux linkage will vary according to that current will vary. Initially current is very high because of inrush current, then it lies within 10 to 20 ampere.

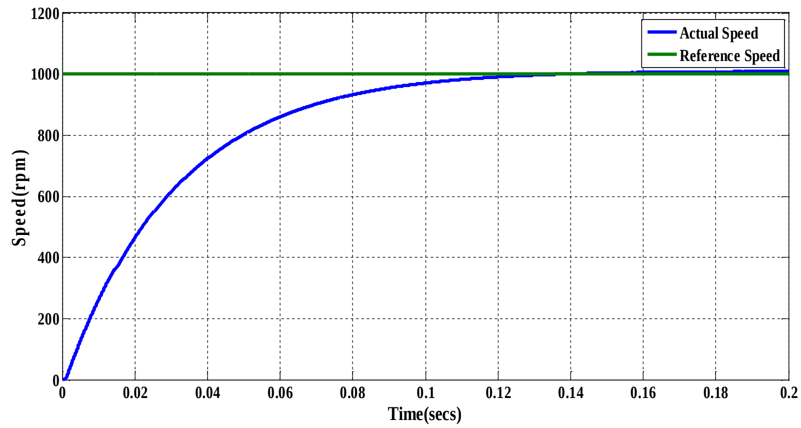


Figure4.5 Speed v/s Time characteristics

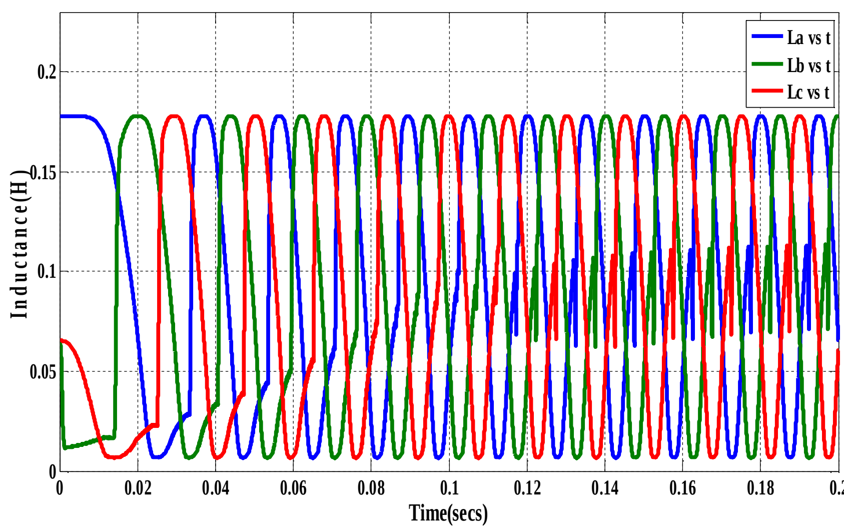


Figure.4.6 Inductance v/s Time characteristics

Here the relation between the speed and inductance is that when the actual speed will track the reference speed at that moment the inductance remains constant. Initially inductance gets varies when it track at that moment inductance gets settle down and remains constant.

Figure 4.6 shows that the inductance of stator phase winding is the function of angular position of the rotor. It can also be observed that the unaligned inductance is 0.8 mH and aligned inductance is 18 mH.

4.3 Modelling Four Phase Switched Reluctance Motor Drive:

It is similar to 3 phases SRM, the only difference is that inside of the power converter block in order to produce 4 phase ac supply it will use 4 half bridge converters. Which helps to produce 4 phase voltages which are 90^0 apart from each other and that becomes the input voltage for four phase switched reluctance motor drive? The advantage is that we can track the reference speed as quickly as possible if the no. of phases increases.

4.3.1 Simulation Results for Four Phase Switched Reluctance Motor:

Various characteristics for 4-phase switched reluctance motor has given below,

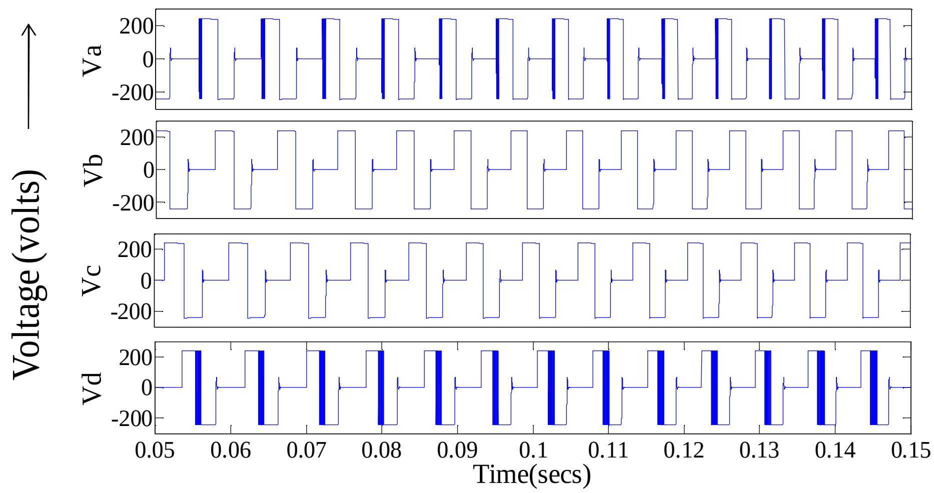


Figure.4.7 Voltage v/s Time characteristics

Here the four output voltage of inverters Va, Vb, Vc and Vd are 90^0 apart from each other, which gives supply to the 4-phase switched reluctance motor.

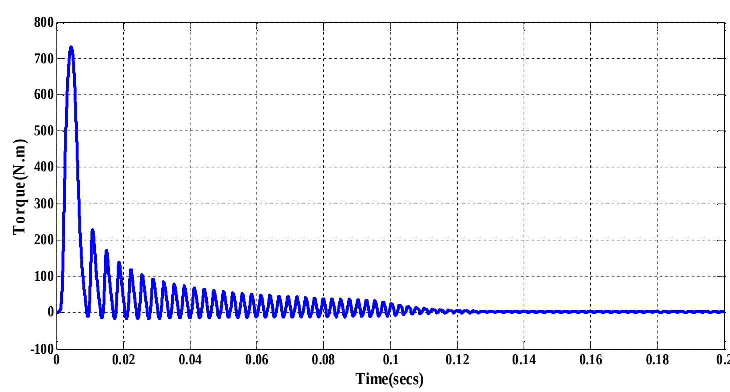


Figure.4.8 Torque v/s Time characteristics

Here torque is directly proportional to square of the current, so, torque is independent of current direction but it depends upon the $\frac{dL}{d\theta}$. If it is positive then torque is positive otherwise the torque is negative. This torque contains lots of noise and harmonics but that must be less than 3-phase switched reluctance motor.

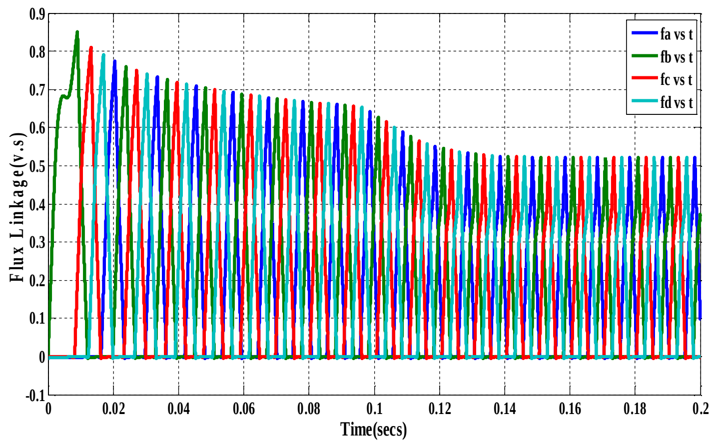


Figure.4.9 Flux Linkage v/s Time characteristics

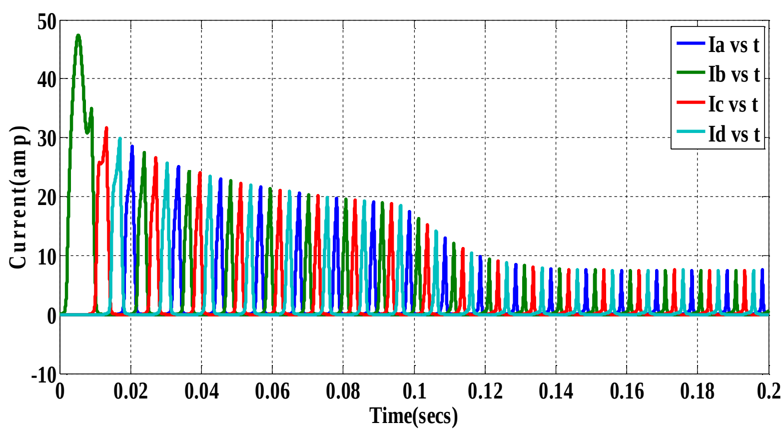


Figure.4.10 Current v/s Time characteristics

The flux linkage and currents are proportional to each other so that they will vary almost similarly with respect to time axis. Initially current is very high because of inrush current, then it lies within 5 to 10 ampere.

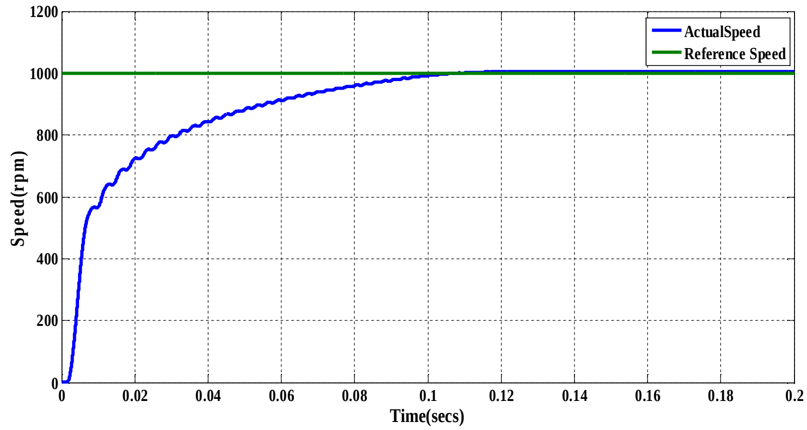


Figure.4.11 Speed v/s Time characteristics

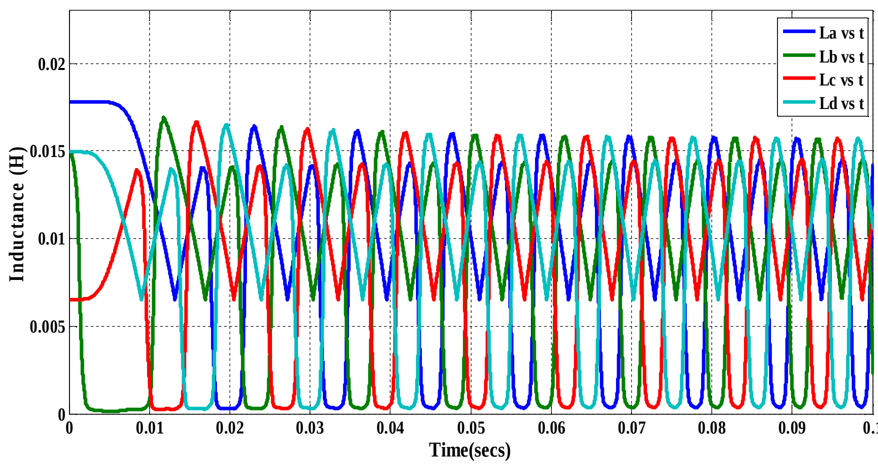


Figure.4.12 Inductance v/s Time characteristics

Here the relation between the speed and inductance is that when the actual speed will track the reference speed at that moment the inductance remains constant. Initially inductance gets varies when it track at that moment inductance gets settle down and remains constant. As it's a 4-phase machine so, it consists of four inductances having some phase difference. But this will fluctuate till actual speed track the reference and finally its settle down. As it is a 4-phase switched reluctance motor, so in this case the reference speed will track the actual speed more quickly in comparision to 3-phase switched reluctance motor. In this case the actual speed will track the reference speed nearly 0.1 sec.

Figure 4.12 shows that the inductance of stator phase winding is the function of angular position of the rotor. It can also be observed that the unaligned inductance is nearly 0.8 mH and aligned inductance is 17 to 18 mH.

4.4 Modelling Five Phase Switched Reluctance Motor Drive:

Here the speed controller is nothing but the PID controller whose input is the speed error that is the difference between the speed reference and the filtered speed feedback signal and its output is unmodified torque command. Then that torque command goes to current command controller and feedback from position sensor gives rise to reference current that compare with the actual current signal that will feedback from SRM output gives the current error signal that goes to hysteresis band controller. That signal acting as the gate signal for converter. A dc supply has given to converter that converts to 2 level ac signals. Here we use 5 half bridge converters in order to produce 5 phase ac signal. That should be the input for switched reluctance motor. At switched reluctance motor output we got flux linkage, current, output torque as well as actual speed of motor. It helps to produce 5-phase voltage which is 72^0 apart from each other. The advantage is that we can track the reference speed as quickly as possible if the no. of phases increases.

4.4.1 Simulation Results for Five Phase Switched Reluctance Motor:

Various characteristics of 5 phase switched reluctance motor has given below,

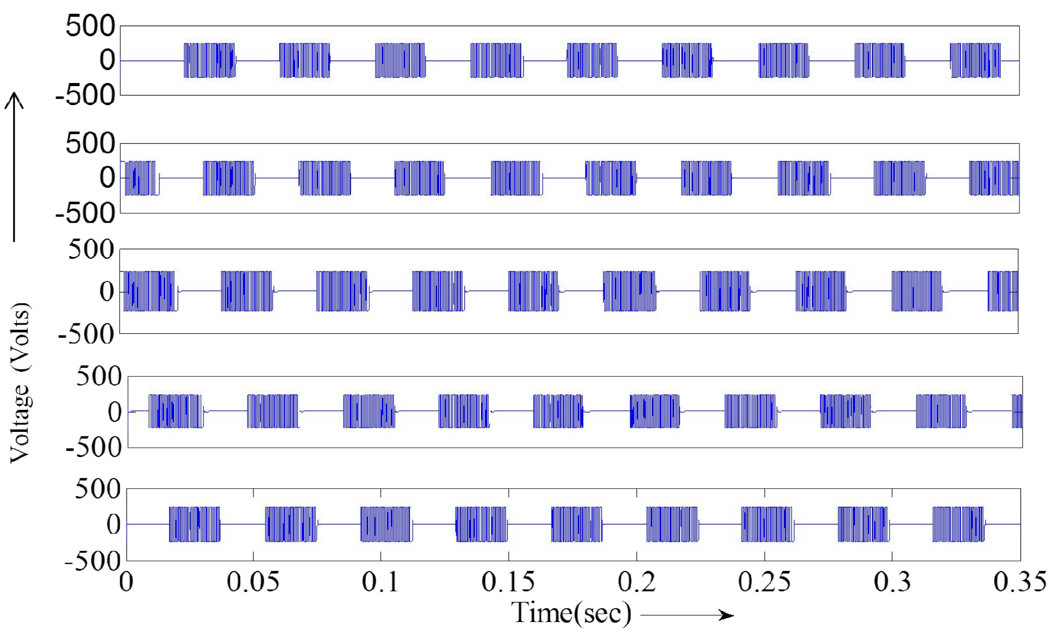


Figure.4.13 Voltage v/s Time characteristics

Here the 5 output voltage of inverters Va, Vb, Vc, Vd and Ve are 72^0 apart from each other, which gives supply to the 5-phase switched reluctance motor.

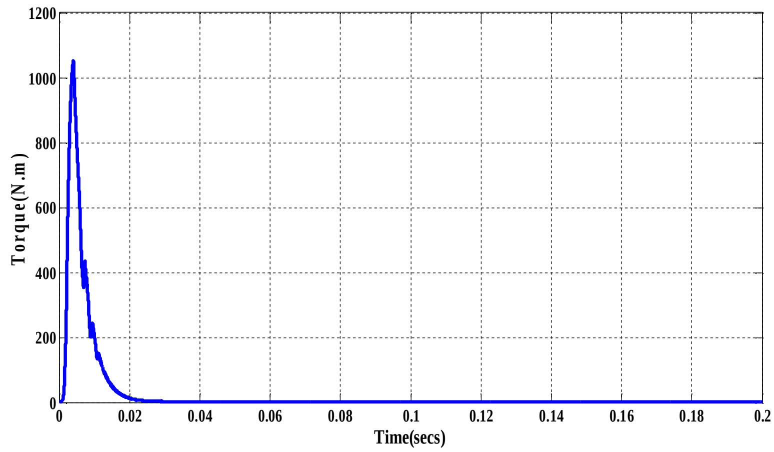


Figure.4.14 Torque v/s Time characteristics

Here torque is directly proportional to square of the current, so, torque is independent of current direction but it depends upon the $\frac{dL}{d\theta}$. If it is positive then torque is positive otherwise the torque is negative. This torque contains lots of noise and harmonics but that must be less than 3-phase and 4-phase switched reluctance motor.

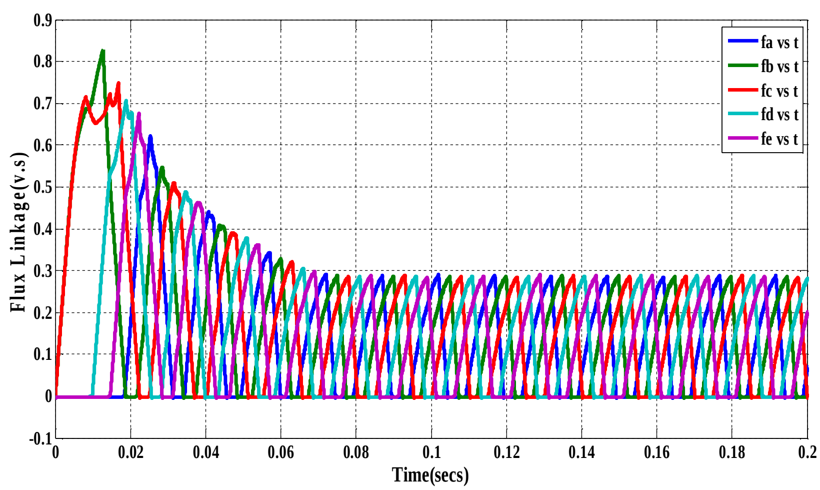


Figure.4.15 Flux Linkage v/s Time characteristics

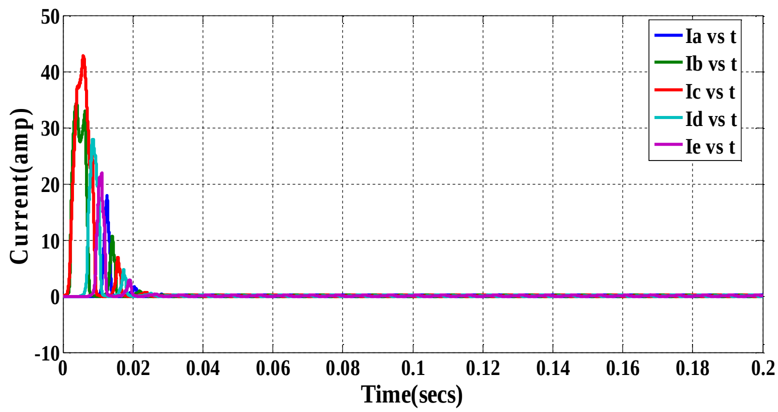


Figure.4.16 Current v/s Time characteristics

The flux linkage and currents are proportional to each other so that they will vary almost similarly with respect to time axis. Initially current is very high because of inrush current, then it lies within 5 ampere.

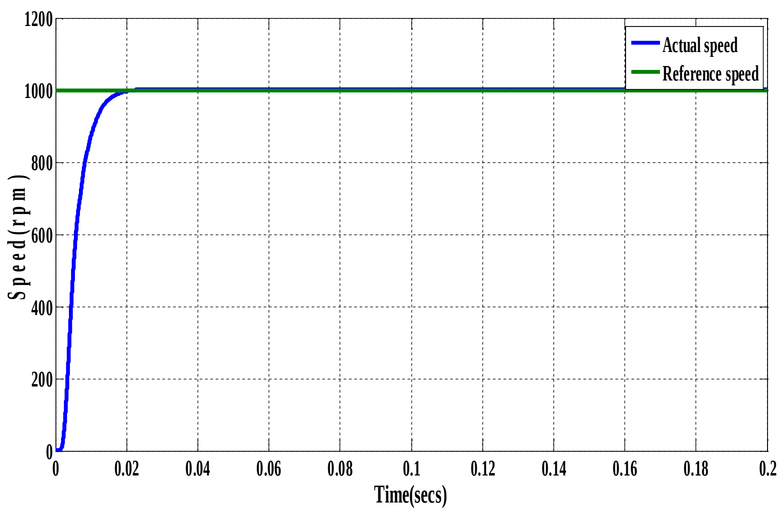


Figure.4.17 Speed v/s Time characteristics

As it is a 5-phase switched reluctance motor, so in this case the reference speed will track the actual speed more quickly in comparision to 4 and 3-phase switched reluctance motor. In this case the actual speed will track the reference speed nearly 0.02 sec.

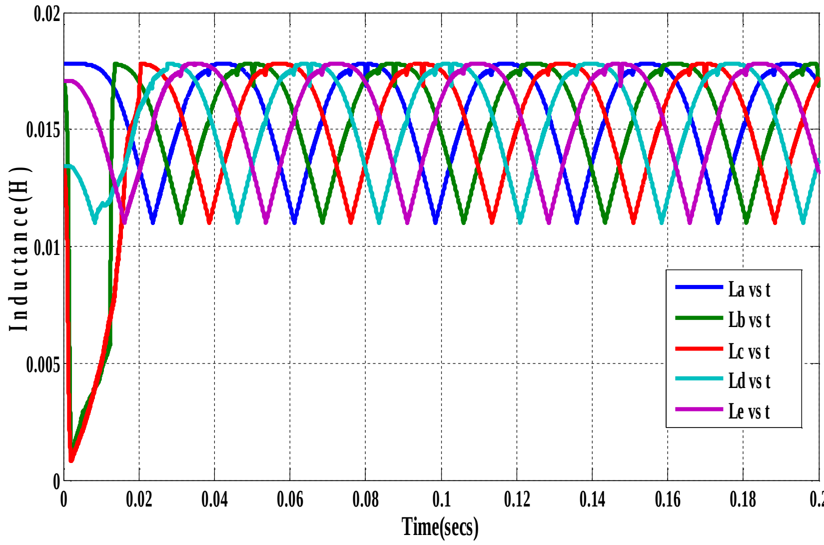


Figure.4.18 Inductance v/s Time characteristics

Here the relation between the speed and inductance is that when the actual speed will track the reference speed at that moment the inductance remains constant. Initially inductance gets varies when it track at that moment inductance gets settle down and remains constant. As it's a 4-phase m/c so it consists of 4 inductances having some phase difference. But this will fluctuate till actual speed track the reference and finally its settle down.

Figure 4.18 shows that the inductance of stator phase winding is the function of angular position of the rotor. It can also be observed that the unaligned inductance is nearly 0.8 mH and aligned inductance is 18 mH.

CHAPTER 5

5. DIRECT TORQUE CONTROL OF SWITCHED RELUCTANCE MOTOR DRIVE

5.1 Introduction

In recent years the frequency control of asynchronous motor is widely used. When we will compare it with the switched reluctance motor then, it has more advantages in respect of cost, efficiency, reliability, Speed control performance, heat dissipation [40]. However, the switched reluctance motor has limited application because of its large torque ripple. Due to large amount of ripple in the torque it produces high noise and vibration. Therefore, in order to minimize the ripple in the torque various techniques have been proposed in switched reluctance motor drives. These techniques are mainly classified into two main categories that is design of motor shape and the optimization of control technique.

By using various mechanical design techniques just like by skewing the rotor, by increasing air gap between the stator and rotor, by pole shaping technique we can be able to minimize the torque ripple [20] [21]. But the main drawbacks of this technique are that it will reduce the maximum achievable torque due to increase in effective air gap.

In juxtaposition to these constructive methods, we can also be able to minimize the ripple in the torque over a wide operating range by using electronic control techniques. The most popular electronic control techniques in order to reduce ripple in the torque includes the supply voltage, turn-on and turn-off angles of the converters and current levels. But this method can also have some limitation that it will reduce the overall torque [23]. So, in order to improve the performance of the switched reluctance motor it is required to apply the advanced control strategy.

In the mid of the 1980s a high performance asynchronous motor frequency control system was developed which is known as direct torque control system or DTC [32]. This method is directly control the torque of the switched reluctance motor by controlling the magnitude of flux linkage and the change in speed of the stator flux vector.

5.2 Direct Torque and Flux Control (DTFC or DTC)

In case of switched reluctance motor the production of the torque depends upon the reluctance principle, where the phase operates independently and in succession. Due to nonlinear characteristics of the magnetic circuit the expression for the phase torque is given by,

$$T(\theta,i) = i\frac{\partial\psi(\theta,i)}{\partial\theta} \quad \text{.........................} \quad (5.1)$$

Where 'θ' is the rotor angular position and 'i' is the phase current. So, from the above equation we can tell that the phase torque '$T(\theta,i)$' is directly proportional to $\frac{\partial\psi(\theta,i)}{\partial\theta}$. So, in order to produce a positive torque the change in the stator flux amplitude must be increasing with respect to rotor position and in order to produce negative torque change in stator flux amplitude must be decreasing with respect to rotor position.

The block diagram representation of the direct torque control technique has given below in figure 5.1. This direct torque control technique consists of three important functions: hysteresis control of torque and flux, an optimal switching vector look-up table and a motor model. In this method the actual or estimated speed is compared with the reference speed, the output of this two is known as error signal. That goes to the speed controller which is nothing but the PID controller whose output gives the reference value of electromagnetic torque which is known as T_{ref}. In this case the reference value of torque and flux can be compared with its actual value and the control signal can be produced by using a torque and flux hysteresis control method. The output of hysteresis band controller has given as the input signal for the vector look-up table. For all the possible stator flux-linkage space vector positions that provides the optimum selection of the switching vectors has given by the switching vector look-up table that is table 5.3. The angle of the calculated flux which determines the region where the flux vector is excited and then the output signal is also passes through the switching table.

The signals of switching table provide the gate pulse to the inverter circuit. So, from this we can conclude that the space vector of inverter is mostly depends upon the three factors.

i. Flux hysteresis control signal.
ii. Torque hysteresis control signal.
iii. The angle of flux vector and the direction of the flux vector rotation.

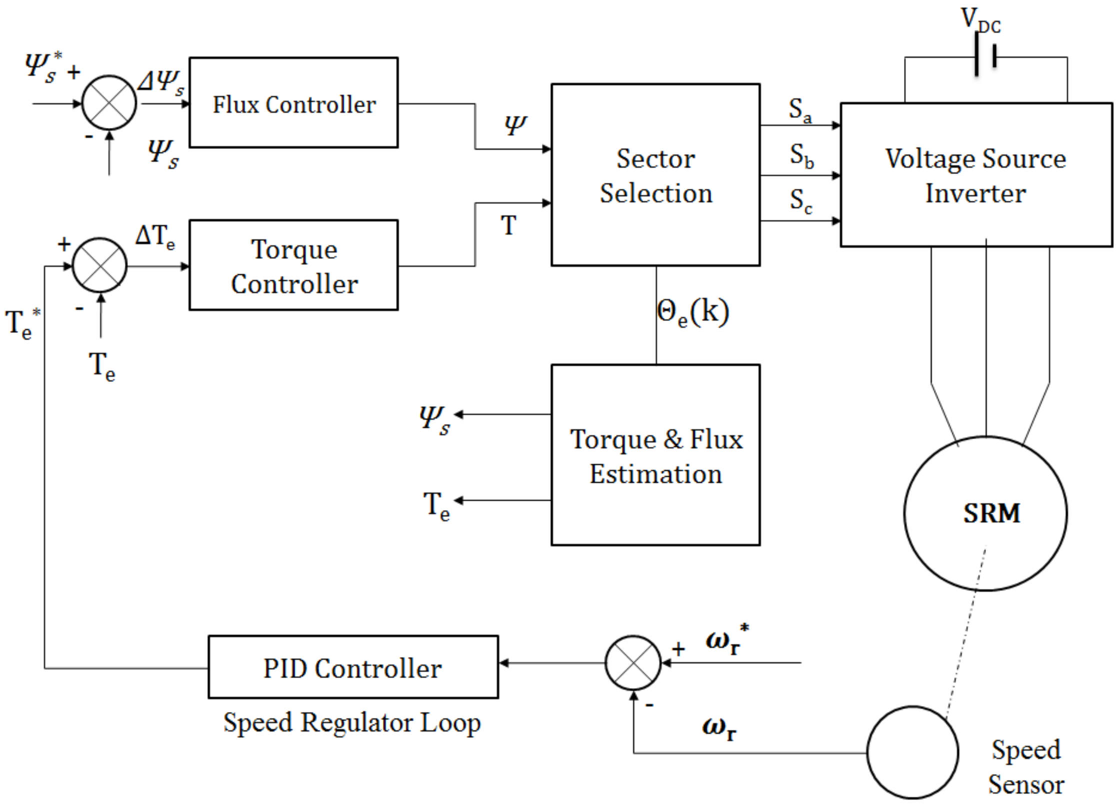


Fig.5.1 Block Diagram of Direct Torque and Flux Control

5.2.1 Mathematical Model of Switched Reluctance Motor Drive :

The dynamic model of the switched reluctance motor is derived by transforming the three-phase quantities into a stationary orthogonal two axis reference frame or we can say it as alpha(α) and beta(β) axes quantities. The transformation of three-phase rotational frame into orthogonal two-phase stationary frame is known as park's transformation. Transformation of three-phase rotational frame to two-phase stationary frame is done by using following equation:

$$\begin{bmatrix} V_{\alpha s} \\ V_{\beta s} \\ V_{0s} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/2 & 1/2 & 1/2 \end{bmatrix} * \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \text{..........................} (5.2)$$

The mathematical model in compact form can be given in the stationary reference frame.

$$\begin{bmatrix} V_{\alpha s} \\ V_{\beta s} \\ V_{\alpha r} \\ V_{\beta r} \end{bmatrix} = \begin{bmatrix} R_s + L_s p & 0 & L_m p & 0 \\ 0 & R_s + L_s p & 0 & L_m p \\ L_m p & \omega_r L_m & R_r + L_r p & \omega_r L_r \\ -\omega_r L_m & L_m p & -\omega_r L_m & R_r + L_r p \end{bmatrix} * \begin{bmatrix} i_{\alpha s} \\ i_{\beta s} \\ i_{\alpha r} \\ i_{\beta r} \end{bmatrix} \quad (5.3)$$

The flux equation of motor is as follows:

$$\begin{bmatrix} \psi_{\alpha s} \\ \psi_{\beta s} \\ \psi_{\alpha r} \\ \psi_{\beta r} \end{bmatrix} = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} * \begin{bmatrix} i_{\alpha s} \\ i_{\beta s} \\ i_{\alpha r} \\ i_{\beta r} \end{bmatrix} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (5.4)$$

Where $V_{\alpha s}, V_{\beta s}, V_{\alpha r}, V_{\beta r}, i_{\alpha s}, i_{\beta s}, i_{\alpha r}, i_{\beta r}, L_s, L_r, L_m, R_s, R_r, \psi_{\alpha s}, \psi_{\beta s}, \psi_{\alpha r}, \psi_{\beta r}$ are $\alpha - \beta$ axes voltages, currents, stator inductance, rotor inductance, mutual inductance between stator and rotor windings, stator resistance, rotor resistance, stator and rotor flux linkages respectively.

5.2.2 Voltage Source Inverter (VSI):

From the above figure that is figure 5.12 S_a, S_b, and S_c are consider as the Voltage Source Inverter's inputs and this S_a, S_b, S_c signal we will get from the sector selection block for which torque hysteresis band, flux hysteresis band and the angle between the flux vector and the direction of the flux vector rotation are the inputs. In order to control the torque and flux command in a conventional switched reluctance motor drive six active voltage vectors are available. In figure 5.13 we will consider S_a, S_b, and S_c are the switching function which may either logic '0' or logic '1'. In this figure the lower switches are always in the complementary state in order to prevent the inverter from short circuit. When the state of the switch is '1' then we consider it as 'on' and when it is '0' we consider it as 'off'. Therefore there are eight possible inverter output which can supply voltage to the switched reluctance motor [25].

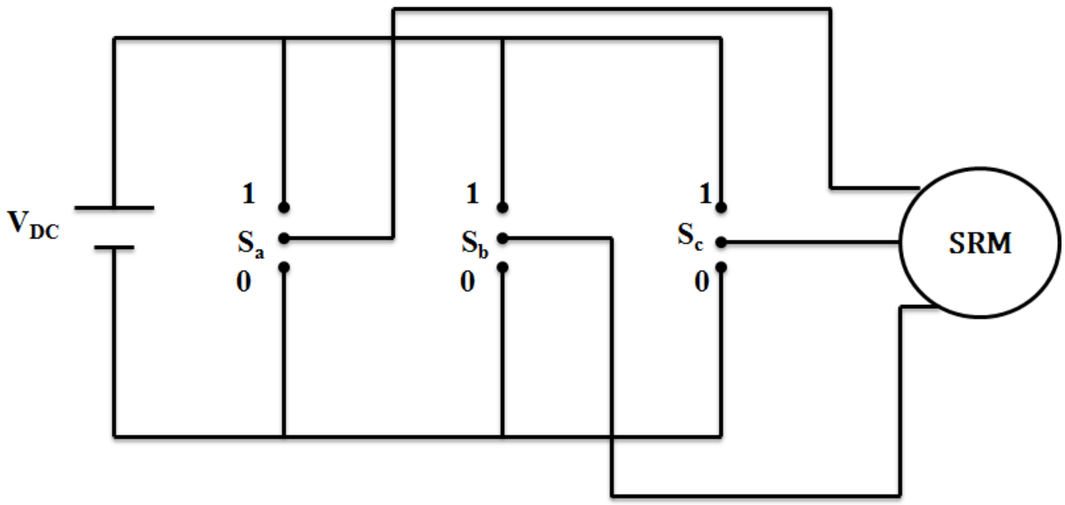


Fig.5.2 Two-level Voltage Source Inverter

If we will consider that the inverter will generate a symmetrical star connected phase voltages V_a ,V_b and V_c then it must satisfy the following condition.

$$V_a + V_b + V_c = 0 \qquad (5.5)$$

If we will write the phase voltages in terms of switching states then, the equation is given by,

$$\vec{V_s} = \frac{2}{3} V_{dc} \left(S_a + S_b e^{j\frac{2\pi}{3}} + S_c e^{-j\frac{2\pi}{3}} \right) \qquad (5.6)$$

Where $\vec{V_s}$ is the voltage space vector and V_{dc} is the dc link voltage of inverter.

The above equation can also be represented in terms of matrix and it is given as,

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{V_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} * \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \qquad (5.7)$$

5.2.3 Direct Torque Control Technique And Its Control Objectives:

By using the space vector we can analyze the direct torque control technique. By the help of stator co-ordinate system we can directly calculate and control the torque of the motor. The control method of the switched reluctance motor has following two control objectives:

i. The amplitude of the motor stator flux vector should be constant in order to make the trajectory of the stator flux linkage be sub circular.

ii. By accelerating and decelerating the stator flux linkage vector we can be able to control the torque.

In case of direct torque control of switched reluctance motor drive our main aim is to control the flux linkage and electromagnetic torque directly by selecting the proper switching state of inverter. By doing this we can be able to reduce the loss due to switches and harmonic distortion in the stator currents. For controlling the torque and flux of the switched reluctance motor independently, we need two controlling loops that is flux hysteresis control loop and torque hysteresis control loop.

A) Flux Hysteresis Control Loop:

The flux hysteresis loop control has two levels of digital output which is shown in Fig.5.14 with relations shown in Table 5.2. In this case our main aim is to control the flux error. The difference between the reference flux and actual flux gives rise to flux error. By using a 2-level hysteresis comparator the stator flux will follow the reference value of flux within the hysteresis band. The stator flux in the stationary reference frame $(\alpha_s - \beta_s)$ can be estimated as:

$$\psi_{\alpha s}^{s} = \int \left(V_{\alpha s}^{s} - i_{\alpha s}^{s} R_s \right) dt \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(5.8)}$$

$$\psi_{\beta s}^{s} = \int \left(V_{\beta s}^{s} - i_{\beta s}^{s} R_s \right) dt \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(5.9)}$$

Generally, the stator flux linkage can be obtained from the stator voltage vector as from equation 5.6 and 5.7. By neglecting stator resistance R_s, it may be simplified as:

$$V_S = \frac{d}{dt}(\psi_S) \qquad \text{or} \qquad \Delta\psi_S = V_S \Delta t \qquad (5.10)$$

The change in input to the flux hysteresis controller can be written as:

$$\Delta\psi_S = \psi_S{}^{*} - \psi_S \qquad (5.11)$$

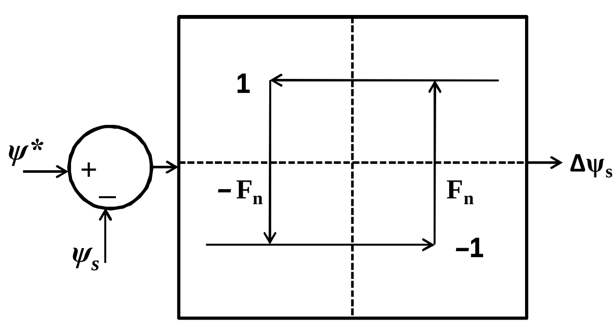


Fig.5.3 Two-level hysteresis controller for controlling the flux error

Fig.5.14 shows the two-level hysteresis controller for controlling the flux error. The flux hysteresis loop controller has two level of digital output according to the relation shown in Table 5.1.

Table 5.1 Switching Logic for Flux error

State	Flux Hysteresis (ψ)
$(\psi_s^* - \psi_s) > \Delta\ \psi_s$	1 ↑
$(\psi_s^* - \psi_s) < -\Delta\ \psi_s$	-1 ↓

B) Torque Hysteresis Control Loop:

In this case the loop consists of a three-level hysteresis controller in order to control the torque error. The difference between the reference torque and estimated torque gives rise to torque error. The torque hysteresis loop control has three levels of digital output which is shown in Fig.5.15 with relations shown in Table 5.2. When the torque hysteresis band is T_n=1 increasing torque, when T_n=0 means no need to change and T_n= –1 decreasing the torque.

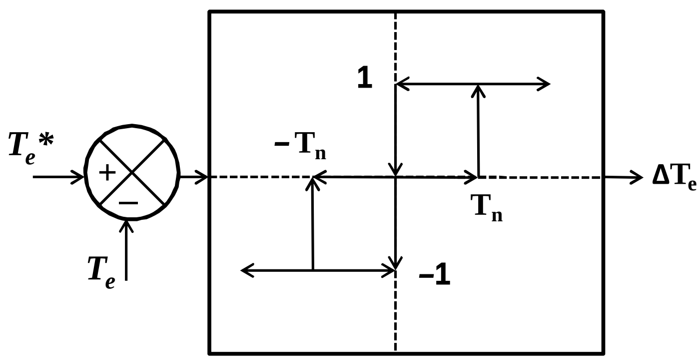


Fig.5.4 Three-level Hysteresis Controller for Control of Torque Error

Table 5.2 Switching Logic for Torque Error

State	Torque Hysteresis (T)
$(T_e^* - T_e) > \Delta T_e$	1 ↑
$-\Delta T_e < (T_e^* - T_e) < \Delta T_e$	0 =
$(T_e^* - T_e) < -\Delta T_e$	-1 ↓

The change in input to the flux hysteresis controller can be written as:

$$\Delta T_e = T_e^* - T_e \quad \text{……………………….. (5.12)}$$

The electromagnetic torque 'T_e' can be expressed as

$$T_e = \frac{3}{2} p \frac{L_m}{\sigma L_s L_r} \vec{\psi}_s \times \vec{\psi}_r \quad \text{………………………………. (5.13)}$$

Where L_m = mutual inductance, L_s = stator self inductance, L_r = rotor self inductance, σ= leakage co-efficient of the motor, ψ_s = stator flux linkage vector and $\psi_r^{'}$ = rotor flux linkage vector in the stationary reference frame.

In the above equation we can observe that the torque of switched reluctance motor is directly proportional to the scalar product between the stator and rotor fluxes in the stationary reference frame.

$$\frac{d\vec{\psi_r}'}{dt}+\left(\frac{1}{\sigma\tau_r}-jp\omega\right)\vec{\psi_r}'=\frac{L_m}{\sigma L_s\tau_r}\vec{\psi_s} \quad \text{(5.14)}$$

Where $\tau_r=\frac{L_r}{R_r}$ is the rotor time constant.

In the s-domain the same relationship can be written as

$$\vec{\psi_r}'=\frac{\frac{L_m}{L_s}}{1+s\sigma\tau_r}\vec{\psi_s} \quad \text{(5.15)}$$

The control scheme assumes that during changes in the control of the stator flux, the rotor flux will remain constant. The control scheme can be operated by keeping the magnitude of the stator flux within the hysteresis band. The torque is thus controlled by varying the relative angle between the stator flux and the rotor flux [25].

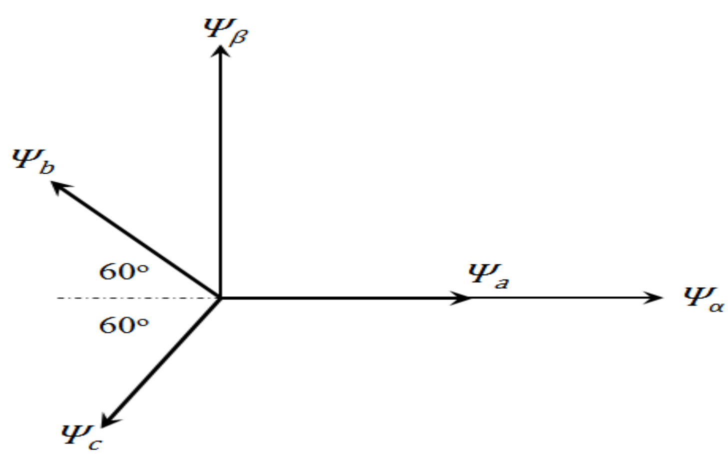


Fig.5.5 α-β axis for motor voltage

In order to resolve these individual phase flux vectors into a single stator flux linkage vector, the flux vector for the three phase switched reluctance motor are transformed onto a stationary orthogonal two axis α-β reference frame as shown in the above figure. By defining the switched reluctance motor stator phase 'a' to lie on the α-axis, the orthogonal flux vector components can be defined as

$$\psi_\alpha = \psi_a - \psi_b \cos 60^\circ - \psi_c \cos 60^\circ \text{ .... } (5.16)$$

$$\psi_\beta = \psi_b \sin 60^\circ - \psi_c \sin 60^\circ \text{ ……………………… } (5.17)$$

The magnitude ψ_s and angle θ_e of an equivalent flux vector are then determined by,

$$\psi_s = \sqrt{\psi_\alpha^{\ 2} + \psi_\beta^{\ 2}} \text{ ………………………………….. } (5.18)$$

$$\theta_e = \arctan\left(\frac{\psi_\beta}{\psi_\alpha}\right) \text{ …………………………….. } (5.19)$$

The instantaneous torque equation for switched reluctance motor is given by,

$$T = p\left(\psi_\alpha i_\beta - \psi_\beta i_\alpha\right) \text{ ……………………… } (5.20)$$

Where p = number of pole pairs, ψ = stator flux component, i = stator current component, α-β = transformation components in the stationary reference frame.

5.2.4 Voltage Vector Switching Selection

The torque hysteresis control loop consists of three level hysteresis controller that is 1,0 and -1 respectively and flux hysteresis control loop consists of two level hysteresis controller that is 1 and -1. According to the figure 5.12 each phase of switched reluctance motor consists of three voltage states that is 1,0 and -1,thus it have total of 27 possible configuration for three phase. In case of direct torque control algorithm for three phase switched reluctance motor it has six possible voltage vector state shown in figure 3. These voltage state vectors are defined to lie in the centre of six zones. At a time only one of the six possible states have chosen in order to keep the stator flux linkage and the torque of the motor within the hysteresis band. If the stator flux linkage lies in the k^{th} zone then, by using the switching vectors V_{k+1} and V_{k-1} the magnitude of the flux can be increased and by using the voltage vector V_{k+2} and V_{k-2} the magnitude of the flux can be decreased. Whenever the stator flux linkage reaches its lower limit in the hysteresis band, it is improved by applying voltage vectors which are directed away from the centre of the flux vector space and vice-versa [20]. Fig.5.13 shows the sectors and voltage. Table 5.3 shows the voltage vector switching selection for Voltage source inverter. Table 5.4 shows the relation between torque and flux due to the application of voltage vectors. When torque is to be increased at that time voltage vectors V_2, V_3, V_4 are applied and when torque is to be decreased at that time voltage vectors V_1, V_5, V_6, $V_0/V_7$are applied. When flux is to be increased at that time voltage vectors V_1, V_2, V_6 are applied and when flux is to be decreased at that time voltage vectors V_3, V_4, V_5 are applied. Voltage vectors V_0 and V_7 do not affect the flux. V1, V2, V3, V4, V5, V6 are the active voltage vectors and V0 and V7 are zero vectors.

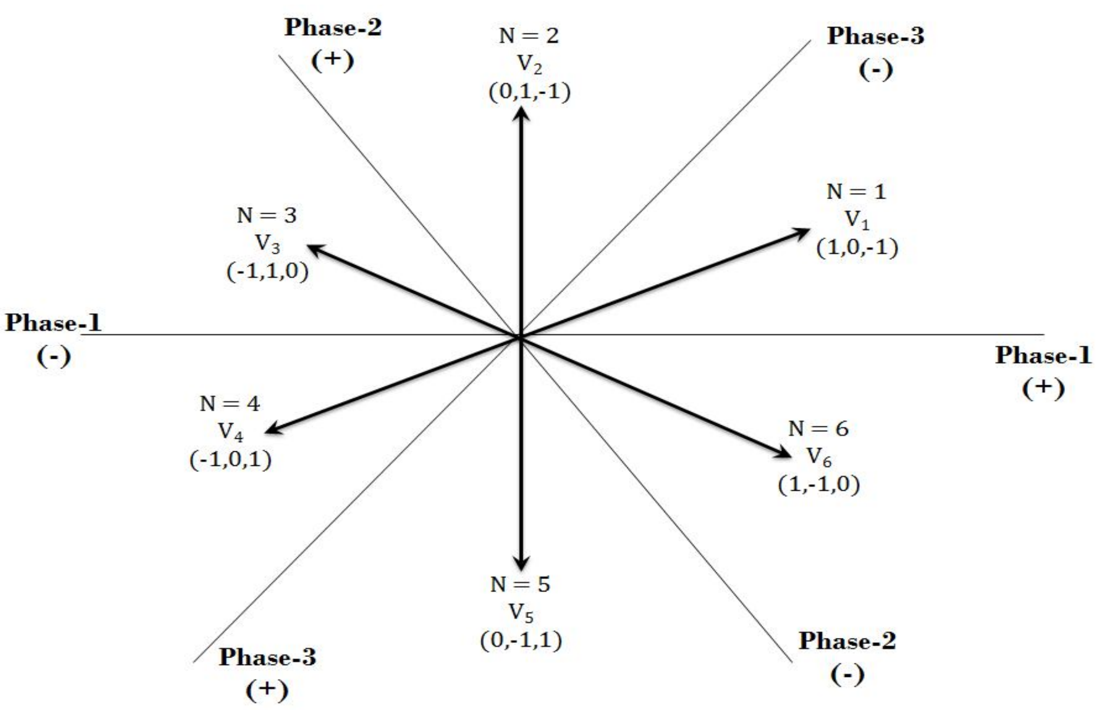


Fig.5.6 Sectors and voltage vectors

Table 5.3 Switching Table of Inverter Voltage Vectors

Hysteresis Controller		Sector Selection θ_e(K)					
Ψ	T	S(1)	S(2)	S(3)	S(4)	S(5)	S(6)
1	1 ↑	V_2	V_3	V_4	V_5	V_6	V_1
	0 ═	V_0	V_7	V_0	V_7	V_0	V_7
	–1 ↓	V_6	V_1	V_2	V_3	V_4	V_5
–1	1 ↑	V_3	V_4	V_5	V_6	V_1	V_2
	0 ═	V_0	V_7	V_0	V_7	V_0	V_7
	–1 ↓	V_5	V_6	V_1	V_2	V_3	V_4

Table 5.4 Flux and Torque Variation Due to application of Voltage Vectors

Voltage Vector	V_1	V_2	V_3	V_4	V_5	V_6	V_0 or V_7
ψ_s	↑	↑	↓	↓	↓	↑	0
$\boldsymbol{T_e}$	↓	↑	↑	↑	↓	↓	↓

5.3 Simulation Results

A 3-phase, 5 HP, 400V switched reluctance motor has taken to control its flux and torque. Machine specifications are given in Appendix-I. A starting torque of 30 N-m, a reference flux of 1.0 Wb and a reference speed of 105 rad/sec or we can say the reference speed of 1000 rpm were set. A PID controller was used in order to track the reference speed.

A) **Results with Load Variation**

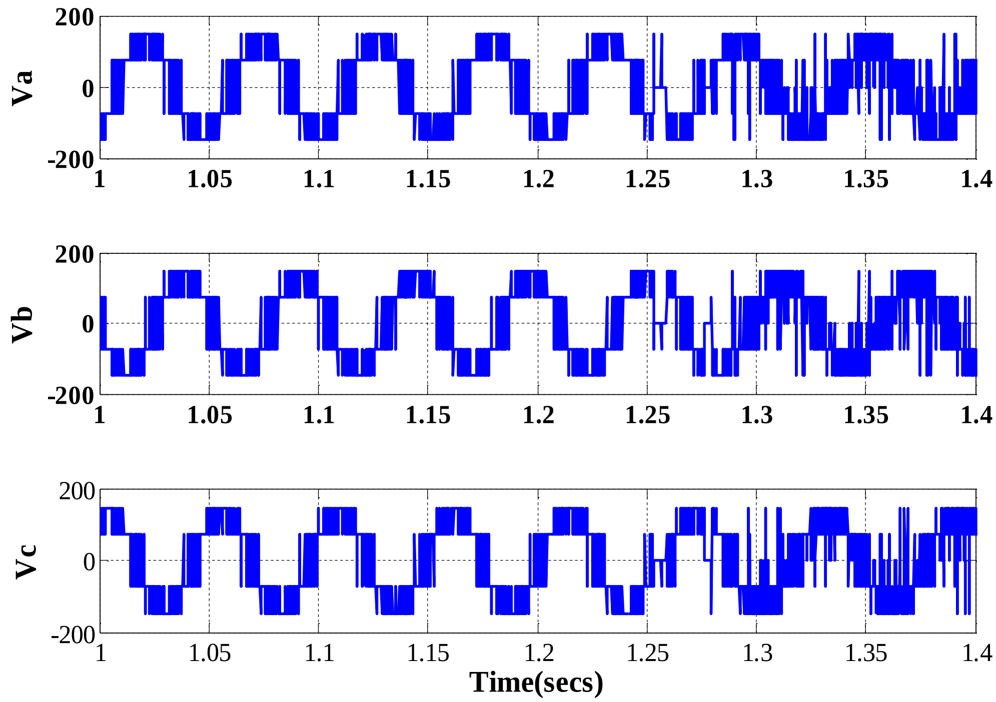


Figure.5.7 Voltage v/s Time characteristics

This is nothing but the output voltage of converter which becomes the input voltage for the three phase switched reluctance motor drive. This shows that the three phase voltages are 120^0 apart from each other.

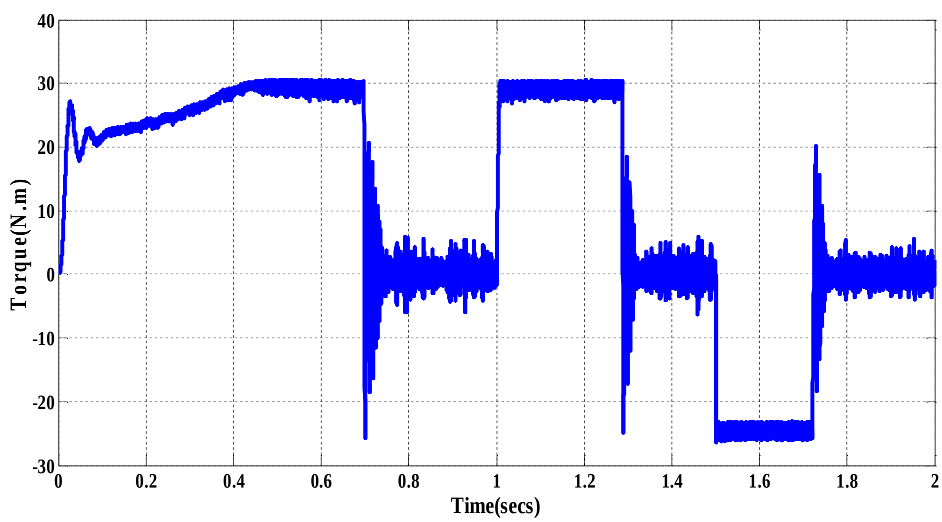


Figure.5.8 Torque v/s Time characteristics

Here torque is directly proportional to square of the current, so, torque is independent of current direction but it depends upon the $\frac{dL}{d\theta}$. If it is positive then torque is positive otherwise the torque is negative. In this case we are applying the load torque also. Here a load torque of 30 N-m was applied at 1sec and removed at 1.3 sec and a negative load torque just above -20 N-m was applied at 1.5 sec and removed at 1.7 sec. Load torque applied between the 1.3 sec to 1.5 sec is 0 N-m. By applying this direct torque control technique we reduced the noise and vibration in the large amount.

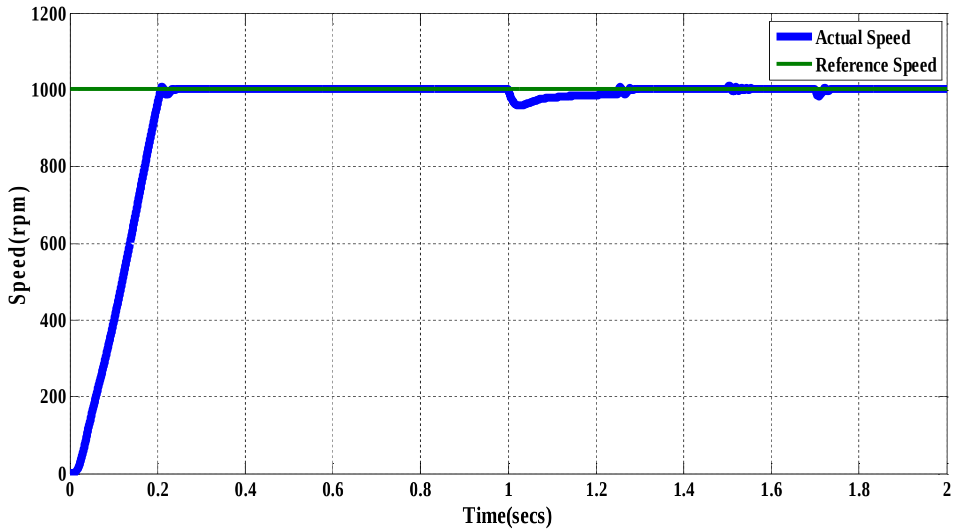


Figure.5.9 Speed v/s Time characteristics

In the above speed v/s time simulation result the actual speed will track the reference speed more quickly around 0.2 sec. In this case we are using the PID controller in order that actual speed will track the reference speed. As load torque of 30 N.m was applied between 1 sec to 1.3 sec so, actual speed just deviates slightly from reference speed at the beginning of 1 sec but after that it will again track the reference speed.

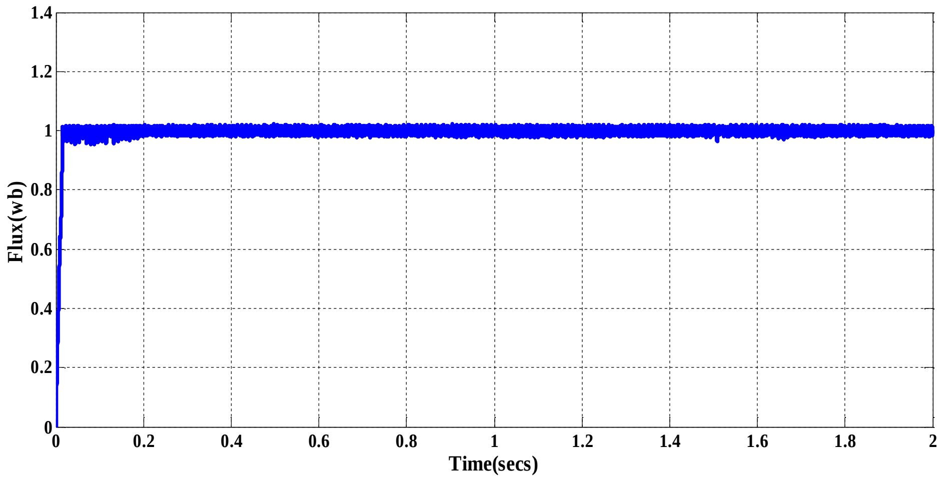


Figure.5.10 Flux v/s Time characteristics

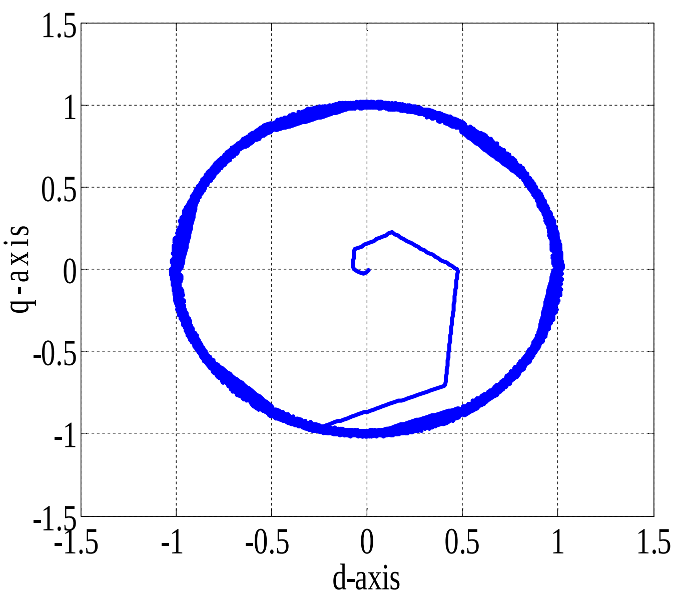


Figure.5.11 Trajectory of stator flux vector

The result of the stator flux linkage control can be seen in figure 5.9 and 5.10 severally plot the amplitude and trajectory of the total stator flux vector. From the above diagram we observed that the amplitude of stator flux vector is relatively constant and it is nearly 1.0 weber. When we are adopting the direct torque control technique in switched reluctance motor drive the flux linkage trajectory is nearly sub-circular in nature.

5.4 Summary

By using MATLAB/SIMULINK environment, simulation models of speed control of switched reluctance motor by can be implemented by using the direct torque control technique. In order to control the limits of the torque and flux two independent torque and flux hysteresis band controllers were used in direct torque control technique. Simulation results were taken by varying the load torque and by varying the reference speed.

CHAPTER 6

6. CONCLUSION AND SCOPE FOR FUTURE WORK

6.1 Conclusion:

- SRM doubly salient structure makes its magnetic characteristics more nonlinear & flux linkage also nonlinear function of stator current & rotor position.

- In comparison to other ac or dc motors we can conclude that switched reluctance motor is very simple in construction from the design point of view.

- With decrease in switching 'on' time the switching frequency increases and as the switching frequency increases the speed of the motor increases with it.

- Even at higher speed this switched reluctance motor provides very good result. This system is more compact, low cost, vibration and temperature change and does not require any frequent maintenance.

- The torque is developed during change of inductance. For constant inductance (unaligned position) torque developed is zero. To get positive torque, voltage should apply during + $\frac{dL}{d\theta}$ region and to get negative torque, voltage should apply during - $\frac{dL}{d\theta}$

region.Therefore exact switching of (turn on and turn off angles) is needed. Simulation helps to get exact switching angles.

- PID controller is used in order to track the reference speed at various load condition.

But in this method the torque produced in switched reluctance motor contains high amount of noise which needs to be controlled.

- By applying the direct torque control technique in the switched reluctance motor we can reduce the ripple in the torque.

- By using direct torque control of switched reluctance motor we can directly regulates the torque output of the switched reluctance motor with in a hysteresis band.

- The torque and flux output can be simply controlled with in a hysteresis band by varying the space vector output.

6.2 Scope for Future Work

- Direct Torque Control (DTC) strategy can be employed to four phase and five phase switched reluctance motor.

- Applying sliding mode control strategy in switched reluctance motor drive.

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